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ELEMENTS OF  
OPTICAL MINERALOGY

By Alexander N. Winchell

ELEMENTS OF OPTICAL MINERALOGY

AN INTRODUCTION TO MICROSCOPIC PETROGRAPHY

*Part I • Principles and Methods • Fifth Edition*

*Part II • Descriptions of Minerals • With the  
collaboration of Horace Winchell • Fourth Edition*

*Part III • Determinative Tables • Second Edition*

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# ELEMENTS OF OPTICAL MINERALOGY

## AN INTRODUCTION TO MICROSCOPIC PETROGRAPHY

by

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FOURTH EDITION ✓

### PART II · DESCRIPTIONS OF MINERALS

With Special Reference to Their Optical and Microscopical Characters

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## PREFACE

During the eighteen years since the publication of the third edition of this work, probably the most important development in mineralogy has been derived from the X-ray study of crystals. This has led to an increase in our knowledge of the crystal structure of minerals, a better understanding of the variations in the composition of minerals, and a revision of the classification of minerals.

The X-ray studies of silicates by Bragg<sup>1</sup> and many others led to their classification as first presented in a textbook in the third edition of this work. With slight modifications, including names of divisions as proposed by Strunz<sup>2</sup> and Fleischer,<sup>3</sup> that classification is extended, in this volume, to all silicates, although it is still true that many rare silicates and even some common ones have not yet been studied sufficiently by X-ray methods to obtain full information regarding their structure; in such cases the classification given here is only tentative.

Since X-ray studies of minerals are so important, a very brief statement of the results of such studies has been included in the descriptions, usually under the heading of structure (abbreviated "Struc.").

In preparing this edition the attempt has been made to keep constantly in mind the concept that a mineral is a (crystal) phase found in nature, and that one phase and therefore one mineral is not necessarily constant or simple in composition. In fact, the more minerals are studied the clearer it becomes that most minerals have compositions which cannot be expressed accurately by any simple formulas because of the variations in composition. It is true that some minerals, like diamond and quartz, have definite and simple chemical formulas, but they are exceptions. Even minerals like rutile and sphalerite practically always contain appreciable quantities of elements not shown in the formulas assigned to them. Thus rutile, which is white like pure artificial  $\text{TiO}_2$ , is unknown in nature; and natural sphalerite normally contains iron, which may amount to 20 per cent or more. However, very often the variations in composition are not so limited as this, and one

<sup>1</sup> W. L. Bragg: *Zeit. Krist.*, LXXIV, 237 (1932); *The Structure of Silicates*, Second Edition, 1932; *Atomic Structure of Minerals*, 1937.

<sup>2</sup> H. Strunz: *Mineral. Tabellen*, 1941.

<sup>3</sup> M. Fleischer: Some Problems in Nomenclature: *Am. Soc. Test. Mat.*, Preprint 117 (1947).

mineral, like plagioclase, may show continuous variation in composition from one formula ( $\text{NaAlSi}_3\text{O}_8$ ) to a different one ( $\text{CaAl}_2\text{Si}_2\text{O}_8$ ). Or one mineral may vary continuously in composition from one formula to several others—for hornblende there seem to be at least eighteen end-member formulas!

This concept that one mineral may vary in composition is a new one; indeed, at the start of this century most mineralogists believed that any one mineral had one fixed composition, and, therefore, plagioclase was considered to be a group of minerals each of which had a definite composition; for example, albite was  $\text{Ab}_1\text{An}_0$ , oligoclase was  $\text{Ab}_3\text{An}_1$ , andesine was  $\text{Ab}_2\text{An}_1$ , labradorite was  $\text{Ab}_1\text{An}_1$ , etc. Consequently, mineral names have been given to end-members and sometimes to intermediate types of such variations while the series or system as a whole unit may have remained unnamed. This situation is illustrated by the names enstatite and hypersthene, applied to parts of the orthorhombic pyroxene series from  $\text{MgSiO}_3$  to  $\text{FeSiO}_3$ ; the name enstenite<sup>4</sup> has been suggested for the entire series. Accordingly, enstenite is the name of a mineral species, and enstatite and hypersthene are the names of certain varieties or subspecies. The name for a mineral species is a name which applies to all variations in composition which are possible in the given phase; it is a name of a natural unit. The varietal names are applied to portions of such a unit whose limits are arbitrary and artificially determined. Nevertheless, such varietal names are useful and fully justified, at least in some cases, as illustrated in the plagioclase series.

The very existence of these natural units seems to have been overlooked frequently by mineralogists. For example, metallurgists know that gold and silver form a continuous series of mix-crystals; mineralogists seem to overlook the fact that the continuous series is illustrated also in nature, as well shown by the metal produced by the National mine in northern Nevada which contained very nearly equal parts of gold and silver.

The development of our knowledge of the variations in composition possible in one mineral and the consequent variations in physical characters is clearly illustrated by the fact that the first edition of this work (in 1909) contained only two diagrams showing the relations between variations in composition and in physical characters (plagioclase and orthoclase—celsian), whereas the second edition (in 1927) contained thirty-nine such diagrams, the third edition (in 1933) fifty-six, and the present edition (1951) more than one hundred twenty.

<sup>4</sup> A. N. Winchell: *Am. Jour. Sci.*, VI, 504 (1923).



This book is necessarily based largely on a compilation of all available data. Free use has been made of the standard publications on mineralogy, including especially:

E. S. Dana and W. E. Ford: *System of Mineralogy*, Sixth Edition, with three appendices, 1892-1915.

C. Doelter: *Handbuch der Mineralchemie*, Vols. I-IV, 1912-1931.

P. Groth: *Chemische Krystallographie*, Vols. I-II, 1906 and 1908.

C. Hintze: *Handbuch der Mineralogie*, Vols. I, II, 1897-1938.

A. Lacroix: *Minéralogie de la France*, Vols. I-V, 1893-1913.

C. Palache, H. Berman, and C. Frondel: *Dana's System of Mineralogy*, Seventh Edition, Vol. I, 1944.

The most important source of summaries of recent literature is to be found in *Mineralogical Abstracts*, Vols. I-X, 1920-1949.

For data on optical properties the preceding volumes are of value and also:

T. Barth and H. Berman: *Chem. Erde*, V, 22, (1930)

H. R. Landolt and R. Bornstein: *Physikalisch-chemische Tabellen*, 5 Aufl., 1923-1936.

E. S. Larsen: Microscopic Determination of the Nonopaque Minerals, *U. S. Geol. Surv. Bull.* 679 (1921).

E. S. Larsen and H. Berman: Microscopic Determination of the Nonopaque Minerals, *U. S. Geol. Surv. Bull.* 848 (1934).

For data on X-ray studies of crystal structure one should consult especially: *Strukturbericht*, Vols. I-VII, 1931-1943, and R. W. G. Wyckoff: *Crystal Structures*, 1948.

It is a pleasure to acknowledge the generous assistance received from many mineralogists in the preparation of this book; for example, Professor D. J. Fisher of the University of Chicago made the important suggestion that Schuster's rule for the sign of extinction angles in feldspars should be applied to all monoclinic and triclinic minerals. Helpful suggestions or data have been received from other colleagues including:

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ALEXANDER N. WINCHELL  
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NEW HAVEN, CONN.  
*January, 1951*

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## ABBREVIATIONS AND SYMBOLS

(Chemical symbols and names of periodicals are not included.)

A, B = optic axes of biaxial crystals.

A (in a chemical formula) = one atom of any metallic element.

$a$  = front and rear coordinate or crystal axis.

$\alpha$  = angle between the positive directions of the  $b$  and  $c$  crystal axes.

Alter. = alterations.

B = birefringence.

B (in a chemical formula) = one atom of any element, usually a metal, in oxides, halides, and sulfides, and an acid-forming element in other compounds.

$b$  = right and left coordinate or crystal axis.

B.P. = boiling point.

Bx = bisectrix.

$\beta$  = angle between the positive directions of the  $a$  and  $c$  crystal axes.

C (after refractive index) = red light (656  $m\mu$ ).

$^{\circ}\text{C}$ . = degrees Centigrade.

$c$  = vertical coordinate or crystal axis.

$\gamma$  = angle between the positive directions of the  $a$  and  $b$  crystal axes.

Char. = characters.

Class. = classification.

Comp. = composition.

D (after refractive index) = yellow light of the D doublet (589  $m\mu$ ).

Diag. = diagnostics.

E = extraordinary ray.

2E = the apparent optic axial angle measured in air.

F (after refractive index) = blue light (486  $m\mu$ ).

F. = fusibility.

G. = specific gravity.

H. = hardness.

2H = the apparent optic axial angle measured in oil.

Hex. = hexagonal.

Incl. = inclusions.

Inver. = inversion.

Isom. = isometric.

Li (after refractive index) = lithium (red) light (671  $m\mu$ ).

$\lambda$  = wave length of monochromatic light.

$m$  = an indefinite number.

$\mu$  = micron; a thousandth of a millimeter.

$m\mu$  = millimicron; a millionth of a millimeter.

Max. = maximum.

Mono. = monoclinic.

M.P. = melting point.

N = index of refraction.

Na (after refractive index) = sodium (yellow) light (589 m $\mu$ ).

$N_E$  = index of refraction for the extraordinary ray.

$N_O$  = index of refraction for the ordinary ray.

$N_X$  = index of refraction for the X ray (fast) =  $\alpha$  of German writers and  $N_p$  of Parts I and III.

$N_Y$  = index of refraction for the Y ray (intermediate) =  $\beta$  of German writers and  $N_m$  of Parts I and III.

$N_Z$  = index of refraction for the Z ray (slow) =  $\gamma$  of German writers and  $N_s$  of Parts I and III.

$n$  = an indefinite number.

O = ordinary ray.

Occur. = occurrence.

Opt. = optic.

Orth. = orthorhombic.

$p$  = an indefinite number.

Phys. = physical.

Prop. = properties.

$r$  = red (light).

$r > v$  (or  $r < v$ ) (after optic axial angle) means that the optic axial angle in red light is greater than (or less than) the optic axial angle in violet light.

Rhom. = rhombohedral.

Struc. = structure.

Tetr. = tetragonal.

Tl (after refractive index) = thallium (green) light (535 m $\mu$ ).

Tric. = triclinic.

Trig. = trigonal.

U.C. = unit cell; U.C. 4 means that the unit cell contains 4 times the formula atoms.

2V = the true angle between the optic axes, or the optic axial angle.

$v$  = violet (light).

X (in a chemical formula) = one atom of an element like S, O, Cl, F (also OH).

X = the vibration direction of the fast ray; also that ray.

$X > Y$  (or  $X < Z$ ), etc. = absorption greater (or less) for the fast ray than for the the intermediate (Y) or slow (Z) ray.

Y = the vibration direction of the intermediate ray; also that ray.

Z = the vibration direction of the slow ray; also that ray.

$\wedge$  = angle; for example,  $Z \wedge c$  = the angle between Z and c.

$>$  = is greater than.

$<$  = is less than.

100, 010, 001, 110, etc. = Miller symbols of one or more crystal planes (or faces).

{100}, {010}, {001}, {110}, etc. = Miller symbols of crystal forms.

$\perp$  = normal to.

$\parallel$  = parallel; this is often omitted, as in the statement: "the optic plane is 010"; or it is replaced by an equals sign, as in " $X = a$ ."

(+) or (-) before 2V (or 2E or 2H) means that the optic sign of the mineral is plus or minus.



## SPECIAL NOTICE

Since this is the first time certain symbols have been used in any volume of this work on optical mineralogy, it is important to emphasize, by repetition, the fact that  $N_g$ ,  $N_m$ ,  $N_p$ ,  $N_o$ , and  $N_e$  of Parts I and III are replaced in this edition of this volume by  $N_z$ ,  $N_Y$ ,  $N_X$ ,  $N_O$ , and  $N_E$ . Furthermore, in Parts I and III, and in previous editions of this volume, the sign of the extinction angle in monoclinic and triclinic minerals (except feldspars) has been considered to be positive if it was measured in the obtuse angle between  $a$  and  $c$ , or  $b$  and  $c$ , and negative if measured in the acute angle. Schuster's rule, which is accepted very generally for feldspars, reverses this, since it requires that, when viewing a section from the direction of the positive octant ( $+a$ ,  $+b$ ,  $+c$ ) toward the negative octant ( $-a$ ,  $-b$ ,  $-c$ ), angles measured by rotating the section clockwise from the extinction position with the slow  $Z$  ray (if possible) north-south to the position with the cleavage, twinning, or crystal edge north-south shall be considered positive and those measured by rotating the section anticlockwise shall be considered negative. In this volume Schuster's rule has been applied to the extinction angles of all minerals. Accordingly, the sign of the extinction angle in this book is given as positive<sup>1</sup> if it is measured to a position in the acute angle between  $a$  and  $c$  (or  $b$  and  $c$ ) and negative if it is measured in the obtuse angle.

Experience suggests that students using Part III should be reminded that many minerals vary in composition and therefore in physical properties; for this reason, such minerals cannot be represented in the refringence tables by any single value but must be represented by a range of values. Each mineral with such a variation of refractive index is entered in the tables at the minimum and also at the maximum value of its refractive index, and the continuous variation between these values is indicated by a line connecting the two. This leads to the condition illustrated on many pages of the tables that a single value of the refractive index ( $N_Y$  or  $N_O$ ) may be found to belong to any one of a score, or more, of minerals. For example, if an unknown mineral is found to have an index ( $N_O$  or  $N_Y$ ) of 1.502, reference to Table IVB, on page 145, will show that it might be antigorite (if optically positive) but it might be phillipsite since one of the vertical lines passing 1.502 shows that phillipsite has an index varying from 1.48 to 1.509, and it might be stilbite, for which  $N_Y$  varies from 1.498 to 1.504, and it might be paraffin, for which  $N_Y$  varies from 1.478 to 1.503; finally, reference to supplementary Table IVB, on page 192, shows that it might be ungemachite. Similarly, if the unknown mineral has an index ( $N_O$  or  $N_Y$ ) of 1.626, reference to page 161 will show that it might be bazzite, but also the vertical lines lead to twenty-two other minerals having an index range which includes 1.626.

Attention should also be called to the fact that diagrams showing the relations between composition and properties are only approximations; in fact, some of the diagrams are based on such scanty and poor data that they must be considered

<sup>1</sup> Of course, there is the very rare exception that the sign is positive when measured clockwise from  $c$  to a position beyond  $a$  and therefore in the obtuse angle.

rather crude approximations. However, even the most accurate diagrams should be used with caution. For example, the diagram for the forsterite-fayalite series of olivine is relatively very accurate, but such an olivine may contain some manganese or zinc, which would modify its properties. Again diagrams for plagioclase are rather accurate, but an error of 3-4 per cent in the composition indicated should not be considered unreasonable, partly because the diagrams are not perfect and partly because they assume that potassium and sodium affect the properties in exactly the same way, an assumption which is only an approximation as to indices and extinction angles and apparently all wrong, in some cases, as to the optic angle.

The sign of elongation of crystals is positive if *Z* (the vibration direction of the slow ray) is parallel with, or less than 45° from, the direction of elongation (assuming elongation in one direction); it is negative if *X* is in this place; and it is plus in some positions of the crystal and minus in other positions if *Y* is in this place—this is expressed as plus-or-minus ( $\pm$ ) elongation. In the case of elongation or extension parallel to a plane, the sign of elongation is positive if *X* is normal to the plane or less than 45° from this position; it is negative if *Z* occupies this position; it is plus-or-minus ( $\pm$ ) if *Y* occupies this position.

The orientation rule,  $b > a$ , is adopted generally for orthorhombic and triclinic minerals, especially for new or rare species. But it seems undesirable to apply it to minerals, like anglesite, of well-established orientation, even though X-ray study indicates that the *a* axis of goniometry should be doubled.

## INTRODUCTION

### DRAWINGS, PROJECTIONS, AND DIAGRAMS

It will be assumed that ordinary drawings of crystals in clinographic or orthographic projection or true perspective will be understood by those who use this book, since they are simple and are fully explained in nearly any textbook of mineralogy.

Certain other types of projection need some explanation, because they do not give a picture of the actual crystal, but they are very useful since they present a graphic expression of symmetry and of all the angular relations of the crystal much more clearly and exactly than any picture.

**SPHERICAL PROJECTION.** In spherical projection the crystal is supposed to have its center at the center of an enclosing sphere, as in Fig. 1. From the common center a line is drawn normal to each crystal face, and this line is continued until it meets the surface of the enclosing sphere. This point of intersection is known as the pole of the given crystal face. The poles of all faces in one zone (that is, parallel to one line in the crystal) are on one great circle on the sphere. Conversely, all faces whose poles are on one great circle belong to one zone in the crystal. A face whose pole falls at the intersection of two or more great circles belongs to two or more zones in the crystal. The angular relations between the faces are retained exactly on the sphere; the angles on the sphere, being the angles between normals to the faces, are the supplements of the actual interior angles between the faces of the crystals. These angles between the normals to the faces are the "normal interfacial angles" commonly recorded in all the literature on the subject.

It is customary to place the crystal so that the vertical axis is normal to the equatorial plane of the sphere; then an orthorhombic crystal is turned so that the *b* axis extends right and left. In that position it will have the pole of 001 at the north pole of the sphere, the pole of 010 at the right side, and the pole of 100 at the front of the sphere, the last two poles, as well as those of all faces of the vertical zone (100, 110, 120, 010,





spherical projection as shown in Fig. 3, is represented in full view in Fig. 4. It is important to note that all great circles of the spherical projection appear as arcs of true circles in the stereographic projection, the only apparent exception being that all great circles passing through both the

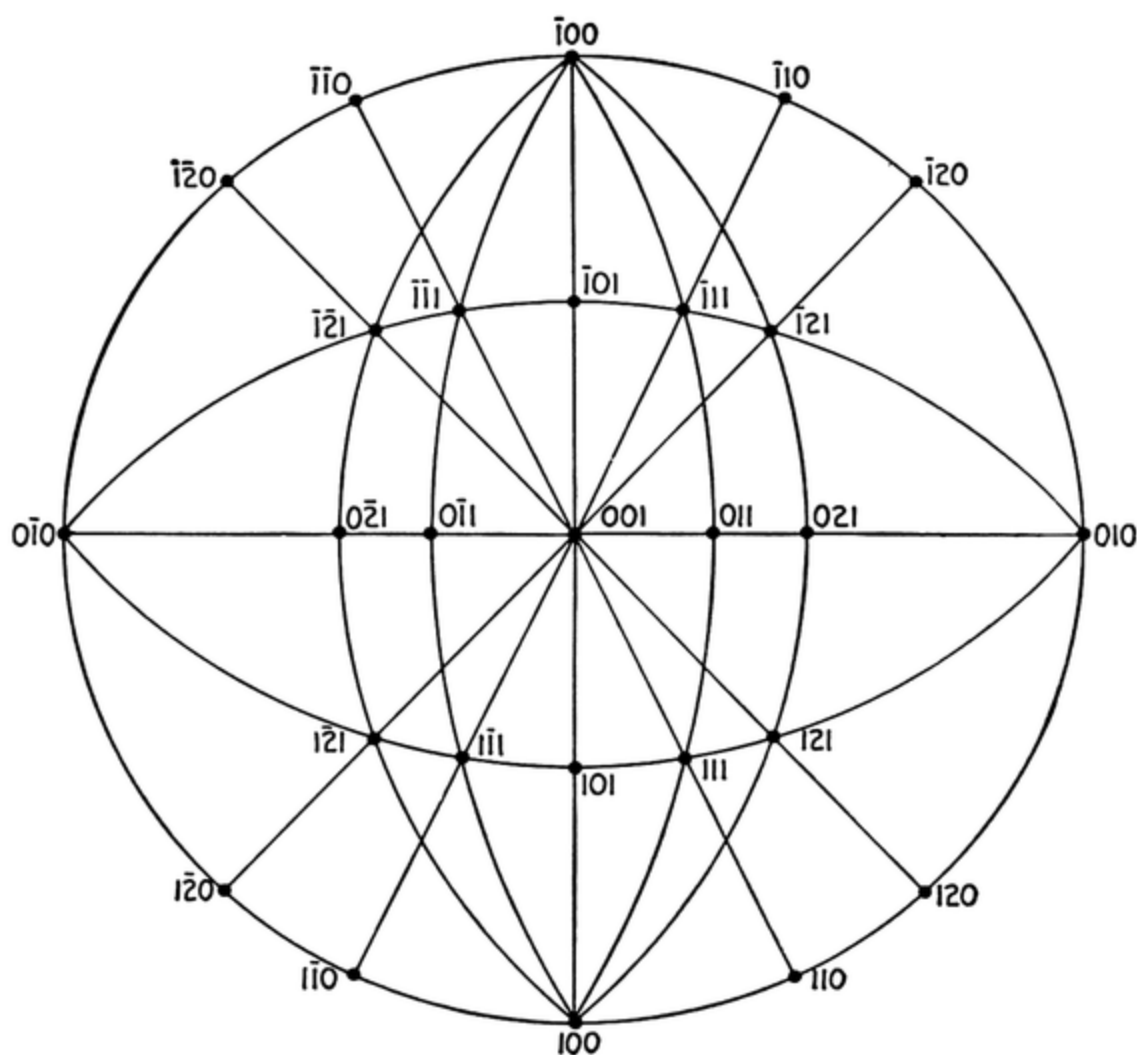


FIG. 4. Example of a stereographic projection.

north and south poles of the spherical projection appear as straight lines in the stereographic projection (but such lines are arcs of circles of infinite radius). The poles of all faces which are parallel to the vertical axis of the crystal are on the equator of the spherical projection and remain at the same points on the boundary circle (equator) of the stereographic projection. The pole of a face normal to the vertical axis of the crystal is at the north pole of the spherical projection and at the center of the stereographic projection. Penfield<sup>2</sup> devised convenient protractors for

<sup>2</sup> S. L. Penfield: *Am. Jour. Sci.*, CLXI, 1 (1901).



plotting and for measuring angles in stereographic projections of definite radius.

The stereographic projection is well adapted to show all the optic properties of a single crystal, as illustrated in its use to show the properties of albite, etc., by Michel-Lévy. It can also express variations in the positions of optic elements in an isomorphous series, but it is not well adapted to show variations in refringence, birefringence, optic angle, or extinction angles in such a series.

**GNOMONIC PROJECTION.** The gnomonic projection may be derived from the spherical projection by assuming a plane tangent to the sphere

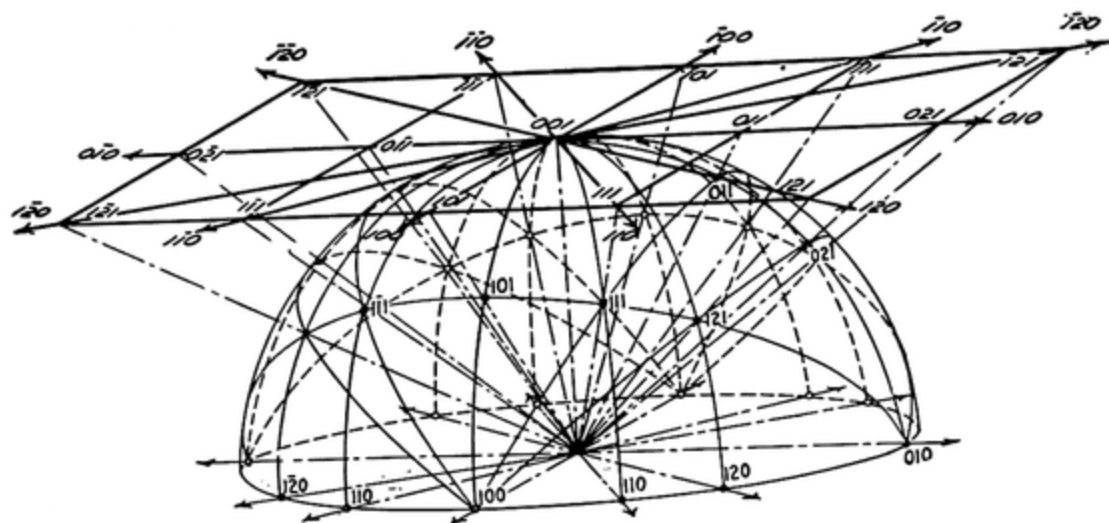


FIG. 5. Derivation of a gnomonic projection.

at the north pole as the plane of projection and projecting from the center of the sphere the pole of each face upon this plane, as shown in Fig. 5. In gnomonic projections all great circles of the spherical projection become straight lines. Therefore, the poles of all faces in any one zone lie in a straight line in the gnomonic projection. The pole of a face normal to the vertical axis of the crystal is at the center of the gnomonic projection. The poles of all the vertical faces of the crystal are at infinite distances from the center; such faces may be indicated by means of radial lines or arrows indicating the directions in which their poles lie. Crystal faces steeply inclined to the horizontal are often indicated in the same way to avoid making too large a drawing. In gnomonic projections the distance of the pole of a given face from the center is equal to the tangent of the normal angle between the base and the given face, considering the distance of the plane of projection from the center of the sphere to be unity. The distance of projection is often conveniently taken as 5 cm.; then a face such as 011 in an isometric crystal has its pole at 5 cm. from the center.

Spherical, stereographic, and gnomonic projections are of value chiefly in studying single crystals; other types of drawings are more useful to illustrate variations in properties in an isomorphous series or system.

**DIAGRAMS.** The ordinary diagram of two coordinates is convenient for showing variations in properties in an isomorphous binary series,

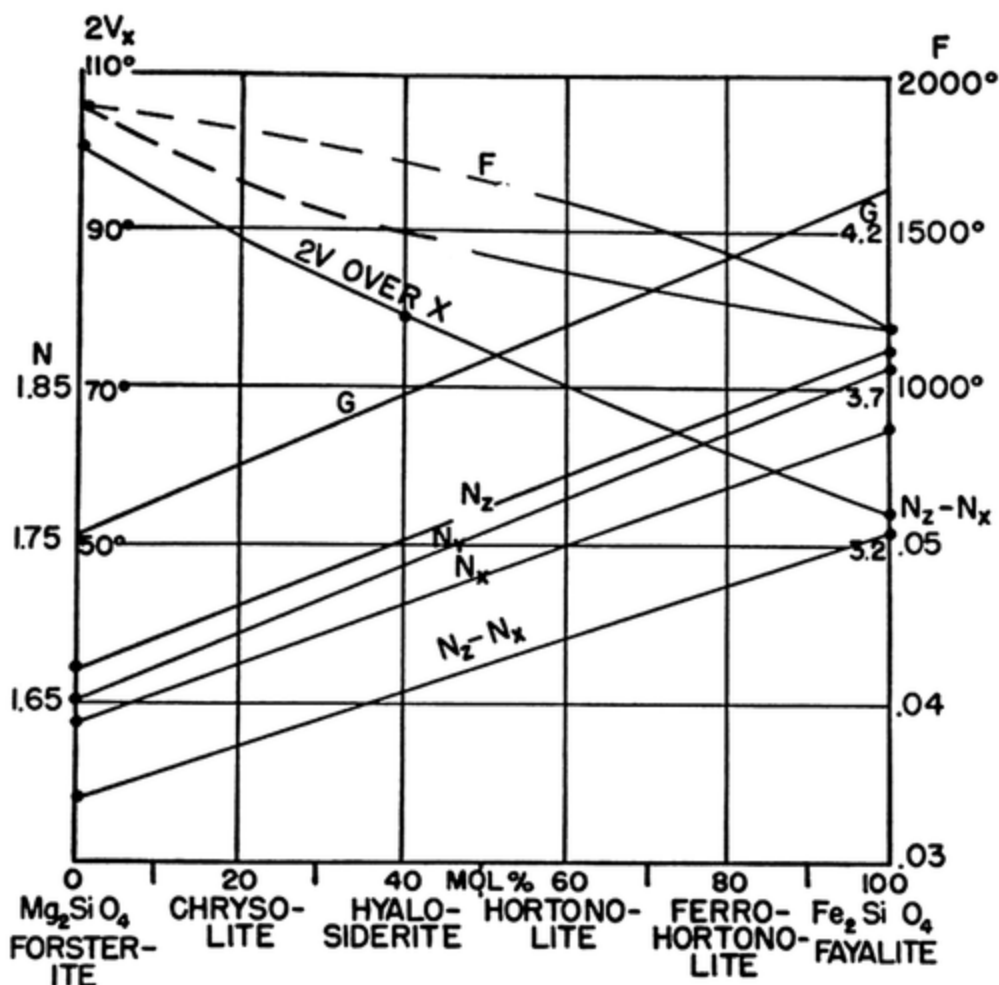


FIG. 6. Variations in properties with variations in composition in a binary series.

that is, in a mineral involving only two molecules, such as plagioclase. One coordinate—usually the horizontal—is taken to represent variation in composition from one simple formula at one end of the line to the other simple formula at the other end of the line. By dividing this line into ten equal parts, each division point represents simple decimal proportions of the two components. Then the other coordinate can be used to represent any property of the substance: an index of refraction, the optic angle, the extinction angle, the specific gravity, the melting point, etc. By placing one or more scales on this coordinate the numerical value of the refractive index or other property can be read directly from the diagram for any composition in the series, and the variations of the



properties with variations in composition can be represented by suitable lines. Figure 6 is such a diagram.

Sometimes in an isomorphous system there are two quite independent kinds of variation in composition. One of the simplest examples of this

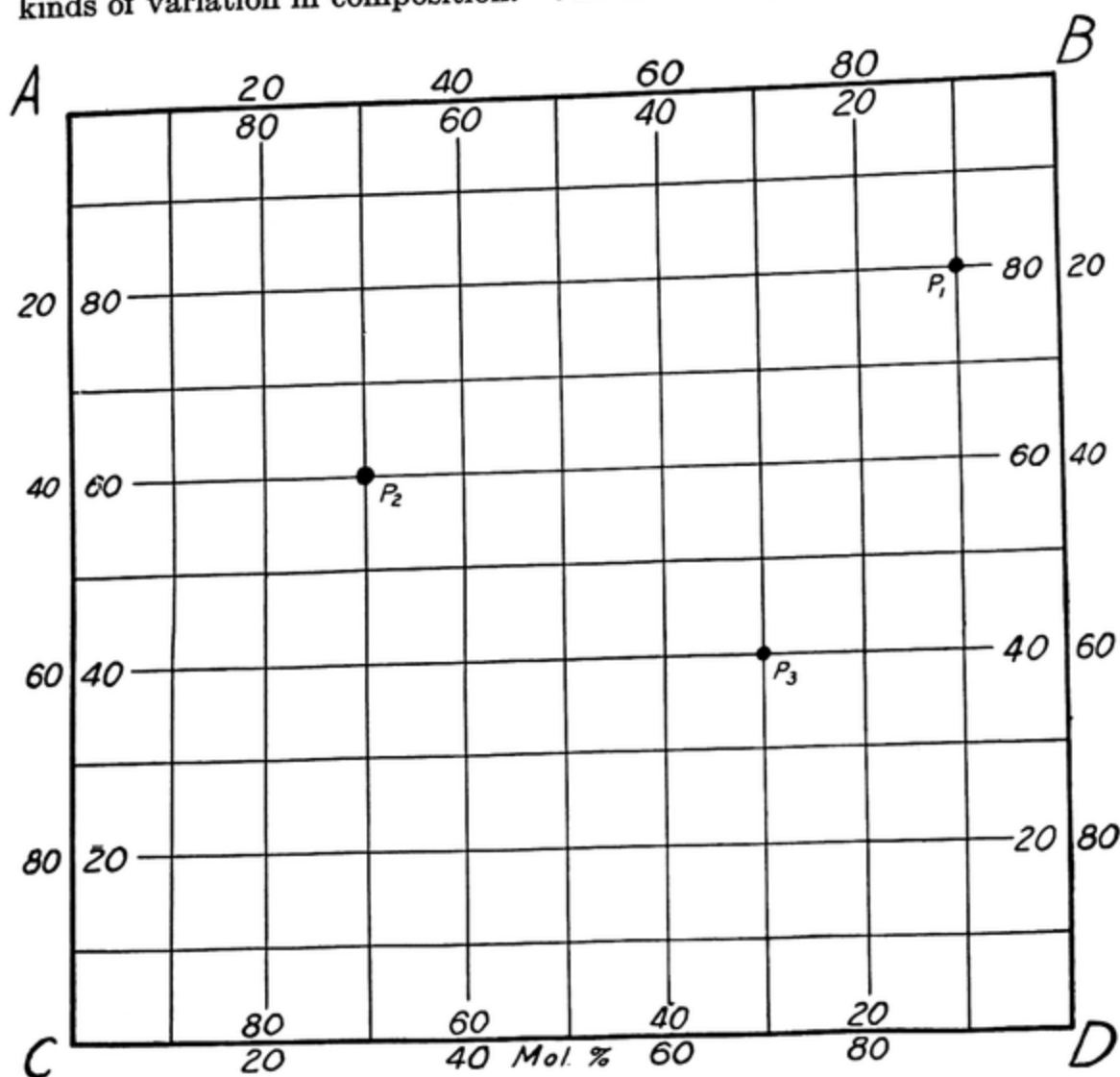


FIG. 7. Diagram for two independent variables leading to four end-members.

is found in the spinel group, in which  $\text{MgAl}_2\text{O}_4$  may vary in one way to  $\text{FeAl}_2\text{O}_4$  and in another way to  $\text{MgCr}_2\text{O}_4$ , the two variations being wholly independent. In such cases each variation in composition should be plotted as one of the usual coordinates, as in Fig. 7, in which  $\text{MgAl}_2\text{O}_4$  may be assumed to be at A; then  $\text{FeAl}_2\text{O}_4$  may be at B, and  $\text{MgCr}_2\text{O}_4$  at C. It is evident that if both these variations are assumed to occur the result will be  $\text{FeCr}_2\text{O}_4$ , and this molecule must be used to complete the square, as at D. Now, if all the sides of the square are divided in tenths and corresponding divisions are connected by straight lines, the whole

area of the square may be divided so that the percentage composition may be easily read at any point. For example, the point  $P_1$  represents 90 per cent of the iron molecules (B and D) and 10 per cent of the magnesium molecules (A and C); it also represents 80 per cent of the aluminum molecules (A and B) and 20 per cent of the chromium molecules (C and D); therefore it represents 90 per cent of 80 per cent or 72 per

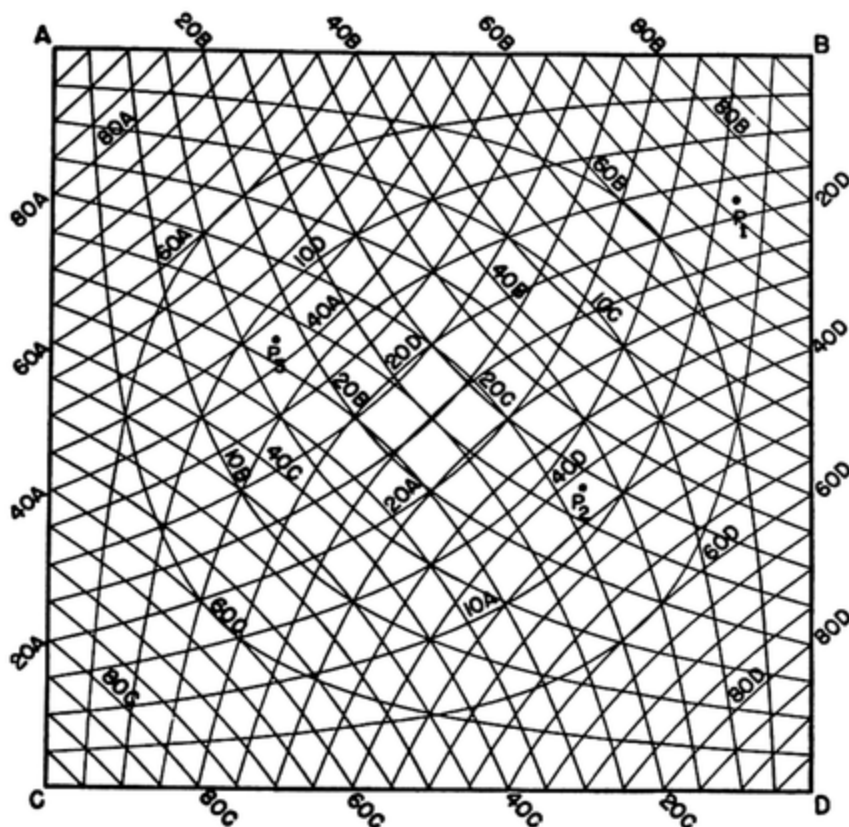


FIG. 8. Diagram for two independent variables showing directly the percentage of each of the four end-members.

cent of B, 10 per cent of 80 per cent or 8 per cent of A, 90 per cent of 20 per cent or 18 per cent of D, and 10 per cent of 20 per cent or 2 per cent of C. Similarly,  $P_2$  represents 42 per cent of A, 18 per cent of B, 28 per cent of C, and 12 per cent of D.

The percentage of each component may be read off directly from such a diagram if a suitable background of curves expressing the composition is supplied, as in Fig. 8. For example, it is clear that point  $P_1$  represents 8 per cent of A, 72 per cent of B, 2 per cent of C, and 18 per cent of D. However, this diagram does not provide any convenient way to subdivide and classify the variations in such a system. Variations in physical properties are not shown as easily on such a diagram as on one for a binary series, but they can be shown, either as lines of equal properties,

like contours, or as measured above the plane of the square in a solid model. It is necessary to use the method of contours in plane figures. An illustration may be found in Fig. 9.

Sometimes a mineral varies in composition only as to one component, but more than one other element may take the place of this component.

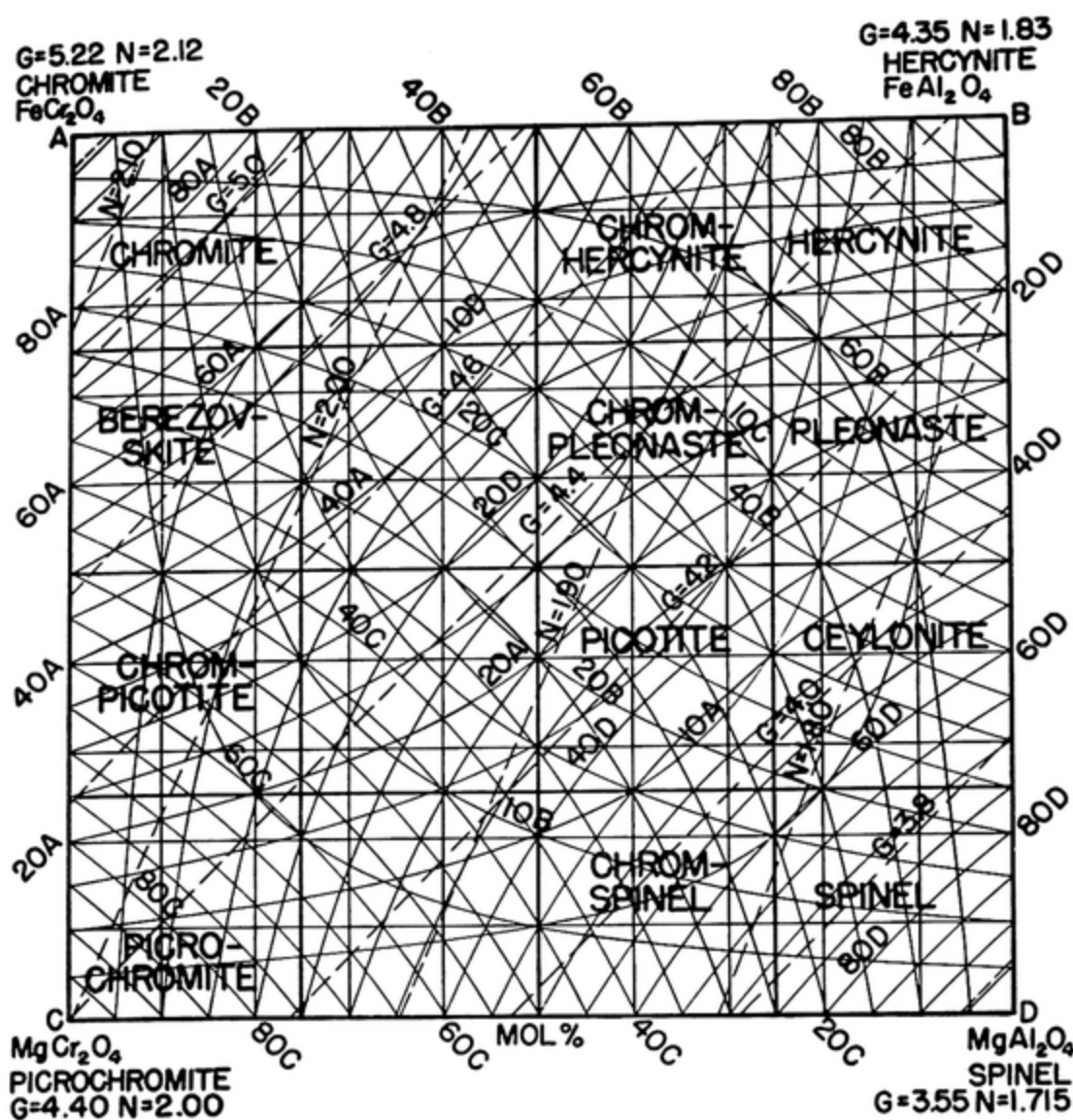


FIG. 9. Variations in properties with variations in composition in a system of four end-members. Data are only approximate.

A simple illustration is furnished by  $\text{MgCO}_3$ , which may vary to  $\text{FeCO}_3$  or to  $\text{MnCO}_3$  or to mix-crystals containing all three of these components. In this instance, there must always be exactly 100 ( $\text{Mg} + \text{Fe} + \text{Mn}$ ) atoms for each 100  $\text{CO}_3$  groups. That is, the sum of  $\text{Mg} + \text{Fe} + \text{Mn}$  is a constant in all parts of the system, and this constant may be taken as 100, for convenience. Such a system may be represented on a triangle,

the three corners of which represent the three simple components, as in any one of the triangles of Fig. 10. Then, by dividing the sides of the triangle into tenths<sup>4</sup> and connecting these points by straight lines, as in the figure, the whole triangle is divided so that the composition represented at any point may be read very easily. For example, the point  $P_1$  represents 40 per cent of A, 10 per cent of B, and 50 per cent of C; the

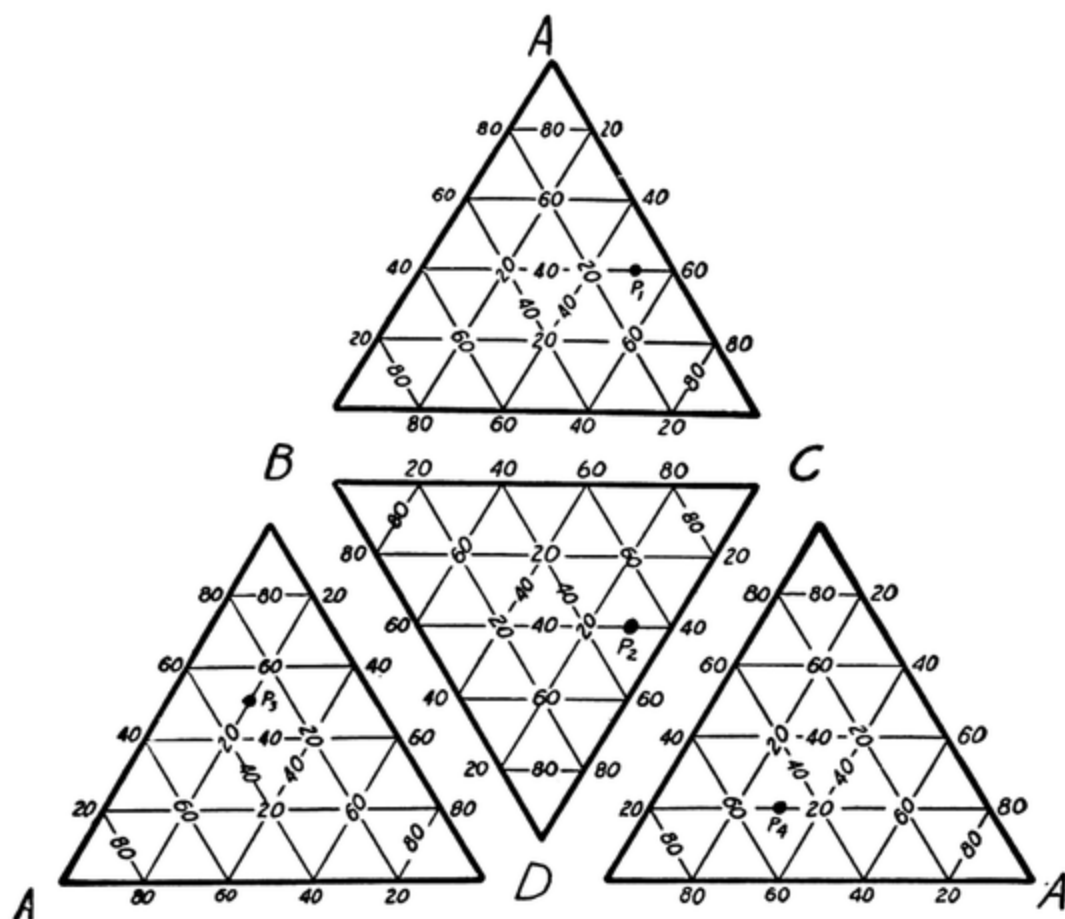


FIG. 10. Diagram for three (and four) end-members.

point  $P_3$  represents 50 per cent of B, 30 per cent of A, and 20 per cent of D. Of course, the physical properties can be shown on such a triangle just as on a square, either by distances above the plane of the triangle in a solid model or by "contours." They are shown by such "contours" in Fig. 11 for the rhodochrosite-siderite-magnesite system.

Sometimes variations in one component of a mineral may lead to three other formulas. For example, chalcantite ( $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ ) may vary to siderotil ( $\text{FeSO}_4 \cdot 5\text{H}_2\text{O}$ ), or to cobalt-chalcantite ( $\text{CoSO}_4 \cdot 5\text{H}_2\text{O}$ ), or to manganchalcantite<sup>5</sup> ( $\text{MnSO}_4 \cdot 5\text{H}_2\text{O}$ ). In this example the constant

<sup>4</sup> For simplicity fifths are used, instead of tenths, in Fig. 10.

<sup>5</sup> Continuity in all parts of this system is probable but has not been demonstrated.

that may be considered 100 is the sum of the atoms of Cu, Fe, Co, and Mn. A tetrahedron is necessary to illustrate all possible mixtures of these four, but, fortunately, in minerals, at least one of the four is usually so inferior in tenor that the point representing the composition is very

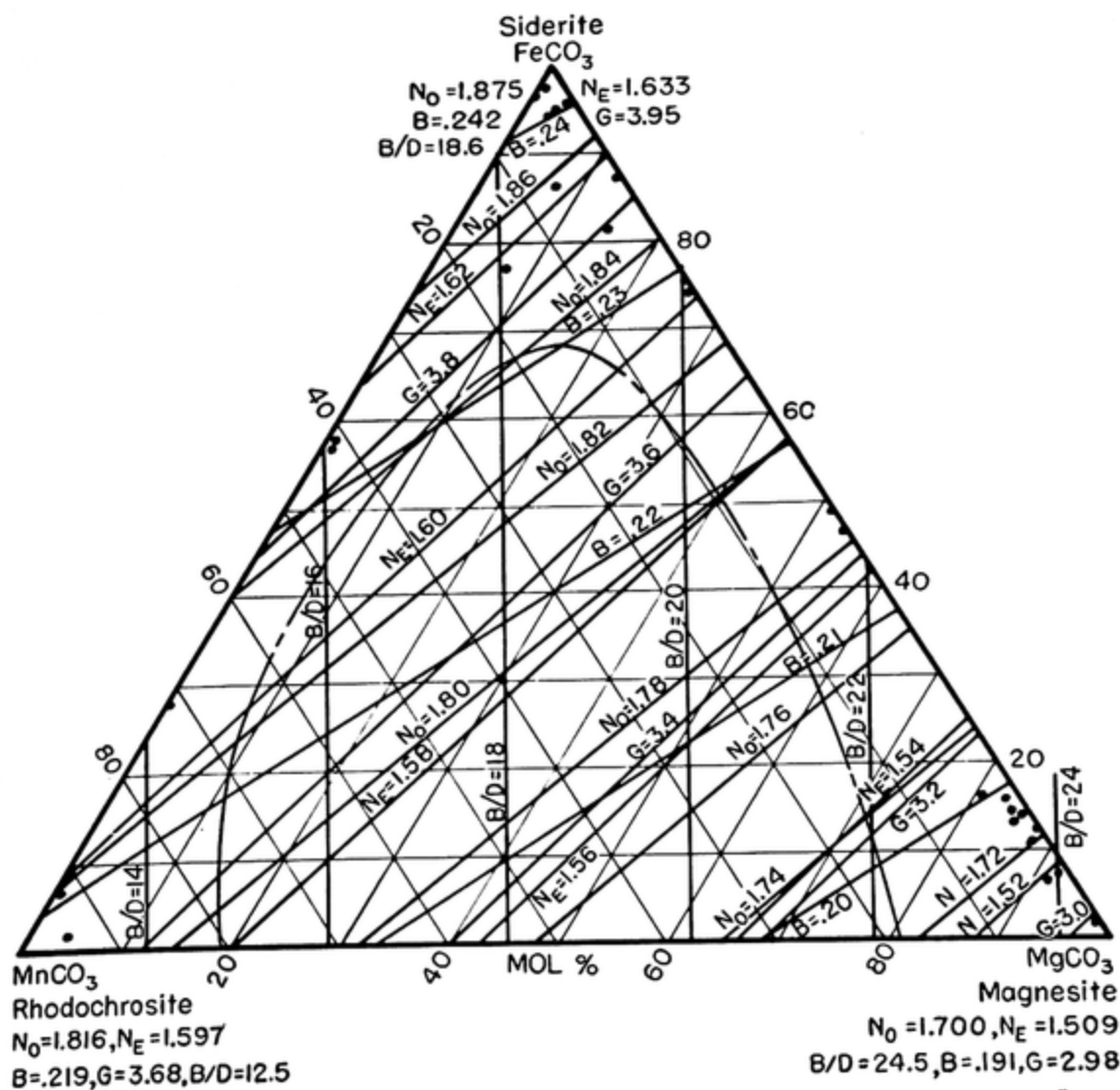


FIG. 11. Variations in properties with variations in composition in a system with three end-members.

near, and, as a close approximation, may be considered to be on, one side of the tetrahedron. The four sides of the tetrahedron may be drawn, therefore, as in Fig. 10, and nearly all the actual cases can be represented on one of the four triangles. The triangle BCD may be considered the base of the tetrahedron, and the other triangles the three sides, having the common apex, A.

However, it may be desirable to show such a four-component system in a tetrahedron, even though the chemical variation may be discon-

tinuous, as in the case of garnets, illustrated in Fig. 12. In the clinographic projection of the tetrahedron the points representing analyzed samples show clearly the essential continuity from pyrope to almandite and thence to spessartite, as well as the discontinuity between these and grossularite.

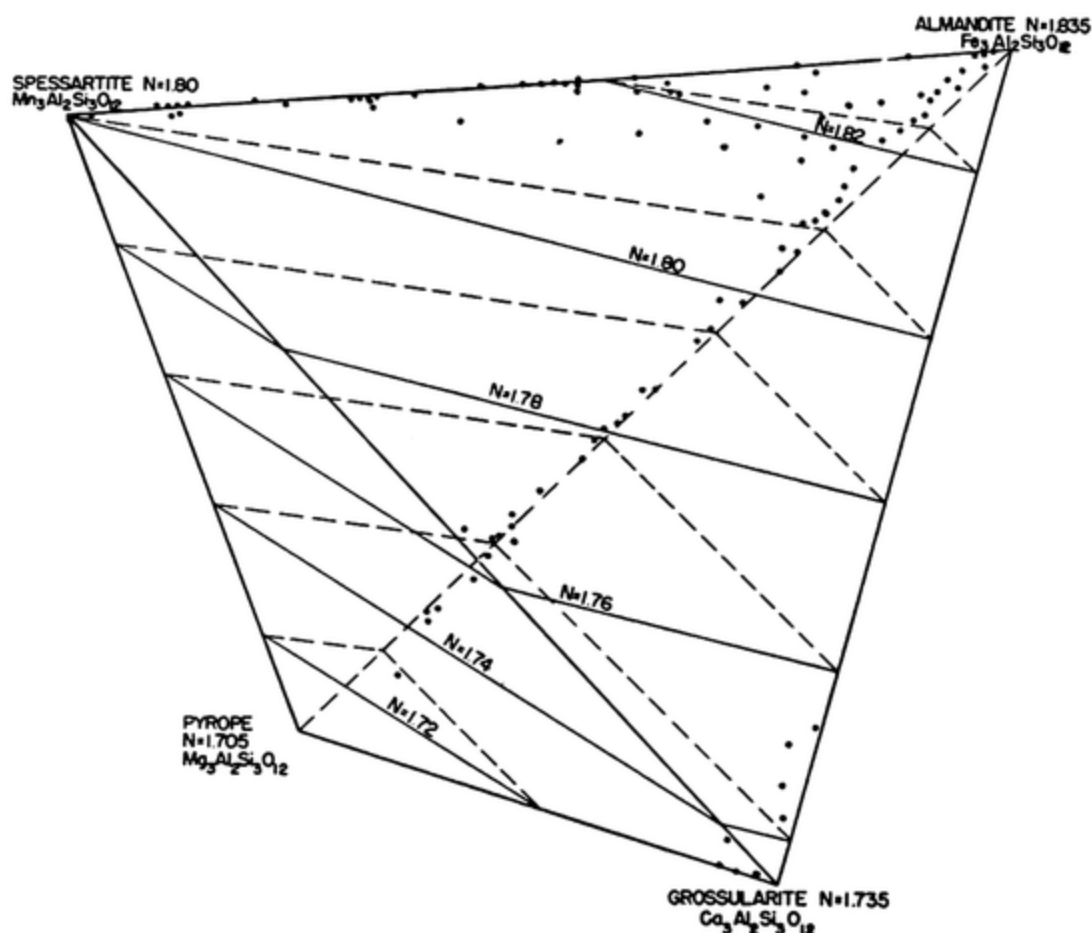


FIG. 12. A tetrahedral diagram for a system with four end-members.

In hornblende (and probably also in montmorillonite) there is variation from two end-members toward a third end-member; here the variation extends just halfway and therefore leads to four (instead of three) end-member formulas, which can be shown on part of a triangle (one corner being cut off) as in Fig. 13. Furthermore, another variation in composition (unrelated to the preceding) can then be shown by drawing part of a triangular prism. This is illustrated in Fig. 14. Of course the variations in physical properties can then be shown on a similar projection, as in Fig. 15.

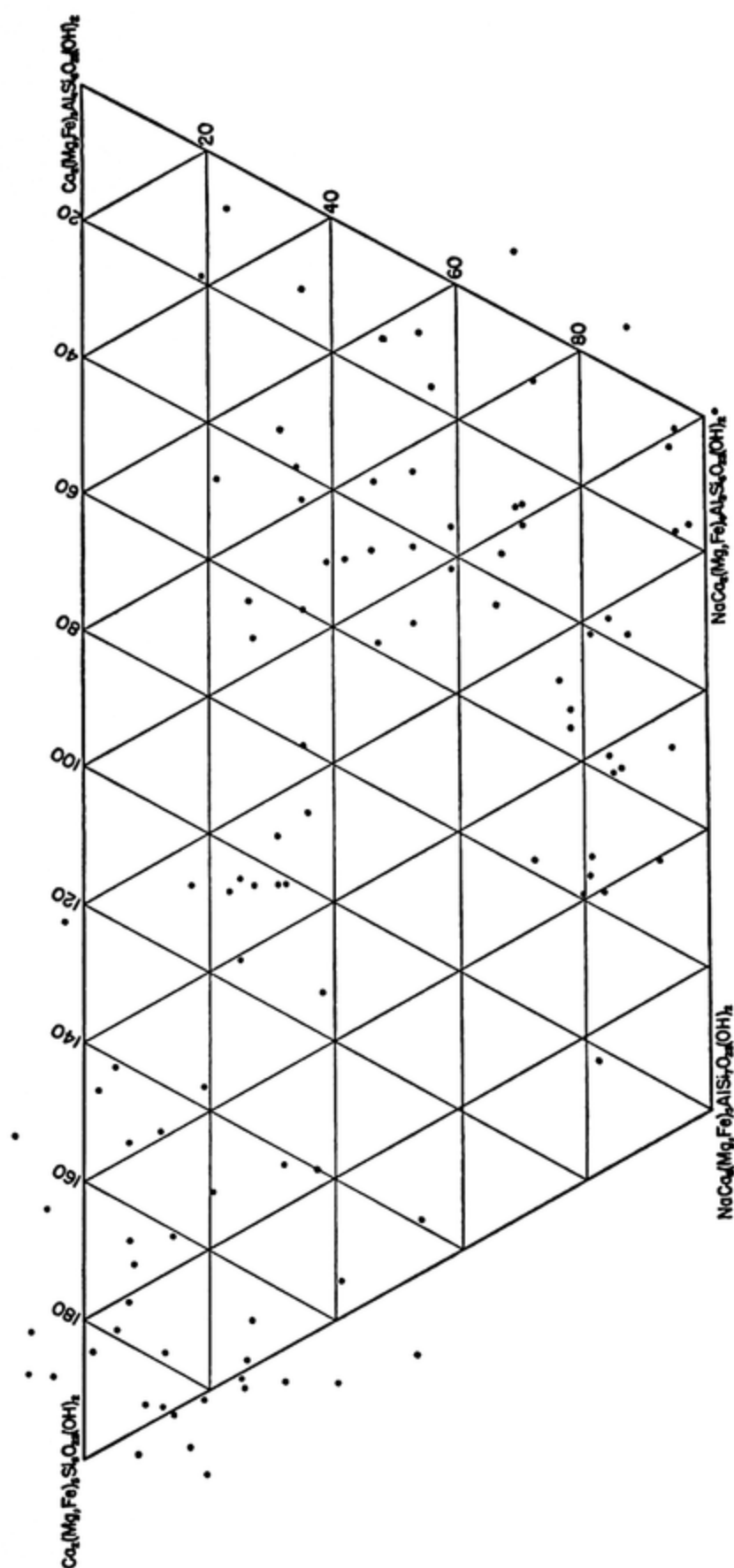


Fig. 13. A partial triangular diagram for four end-members (calcareous hornblende).



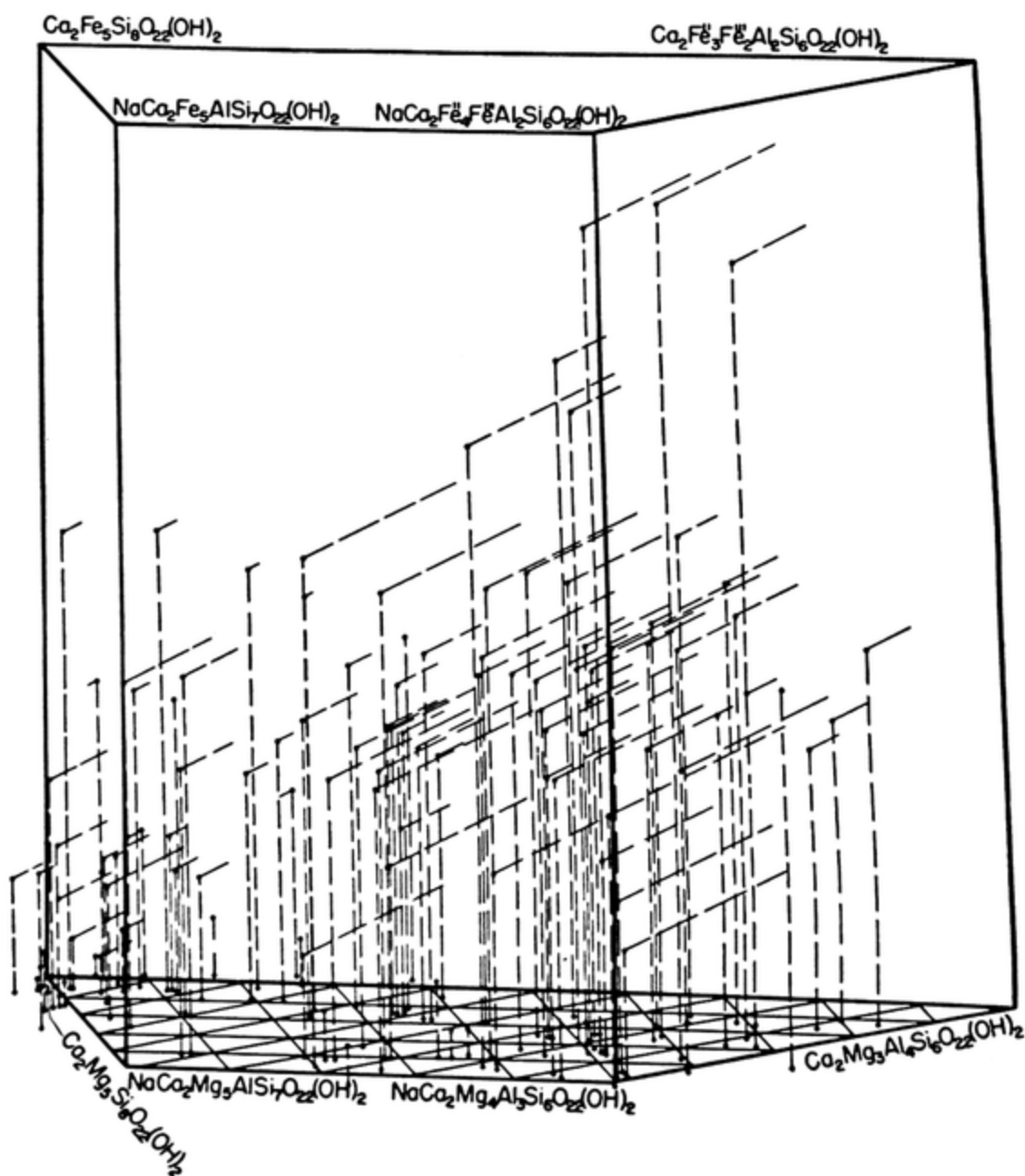


FIG. 14. A partial triangular prism for eight end-members (calciferous hornblende).



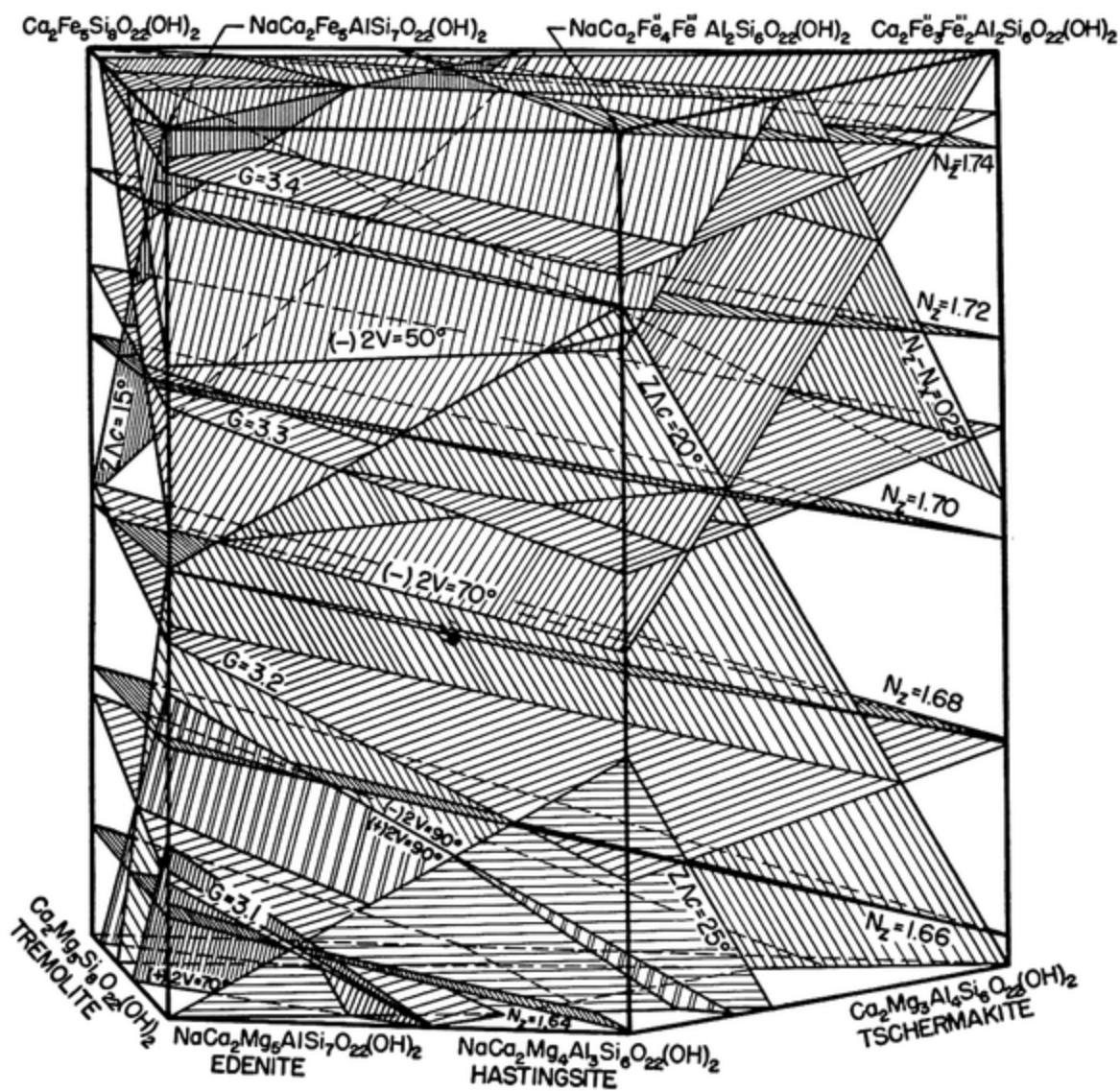


FIG. 15. Variations in properties with variations in composition in a system having eight end-members (calciferous hornblende).



# DESCRIPTION OF MINERALS

## WITH SPECIAL REFERENCE TO THEIR OPTICAL AND MICROSCOPICAL CHARACTERS

### I. ELEMENTS

All transparent or translucent native elements, but only the most important opaque native elements, are included in the following descriptions. The elements are classified on the basis of the type of bonding present, as follows:

1. Elements with metallic bonding.
2. Elements with homopolar bonding.
3. Elements with residual bonding.

#### 1. Elements with metallic bonding

<b>ELECTRUM</b>	<b>Gold</b>	ISOMETRIC HEXOCTAHEDRAL <sup>1</sup>	Au
	<b>Silver</b>	ISOMETRIC HEXOCTAHEDRAL	Ag

**COMP.** The native mineral not only shows the entire range from (nearly) pure gold to (nearly) pure silver but also commonly contains some copper, palladium, rhodium, bismuth, iron, etc.

**STRUC.**<sup>2</sup> Space group *Fm3m*;  $a$  4.0704 Å<sup>1</sup> (Au) to 4.0779 Å<sup>1</sup> (Ag). U.C. 4.

**PHYS. CHAR.** Crystals often octahedral, cubic, or dodecahedral; often in complex groups. Twinning on 111. No cleavage. Highly malleable. H. = 2.5–3. G. = 19.3 (Au) to 10.5 (Ag). See Fig. 16. F. = easy; 1062° C. (Au); 961° C. (Ag). Gold is soluble in aqua regia; silver, in HNO<sub>3</sub>.

**OPT. PROP.** Color and streak vary from gold-yellow (Au) to very pale yellow (Au:Ag = 1:1) to silver-white (Ag); with little silver and some copper the color may

<sup>1</sup> E. R. Jette and F. Foote: *J. Chem. Phys.*, III, 605 (1935).

<sup>2</sup> E. A. Owen and E. L. Yates: *Phil. Mag.*, XV, 472 (1933).

be brassy yellow. Opaque, but gold in thin films transmits green light. Luster metallic. In vertically reflected light gold is light yellow and silver is light creamy white. Refractive index  $N = 0.181$  Na for silver and 0.366 for gold. Percentage reflections<sup>3</sup> for gold: red 85.6, orange 82.5, green 47; for silver: red 93, orange 94, green 95.5.

**OCCUR.** Electrum is found especially in veins in igneous and metamorphic rocks, as in the Porcupine district of Ontario. Gold is also important in some placer deposits, as in California and Alaska. Electrum is often associated with pyrite, galena,

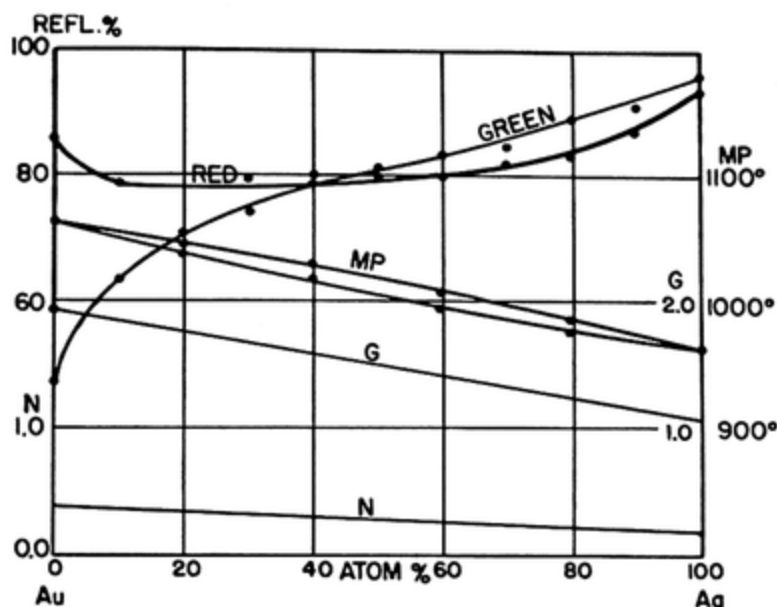


FIG. 16. Properties of electrum.

chalcocite, sphalerite, etc. Silver may be associated with copper, as at Butte, Montana.

## COPPER

### ISOMETRIC HEXOCTAHEDRAL

Cu

**COMP.** Native copper often contains some silver, bismuth, mercury, etc.

**STRUC.**<sup>4</sup> Space group  $Fm\bar{3}m$ ;  $a$  3.607 Å. U.C. 4.

**PHYS. CHAR.** Crystals often modified cubes or in complex groups. No cleavage. Highly malleable.  $H. = 2.5-3$ .  $G. = 8.95$ .  $F. = 1083^\circ \text{C}$ . Soluble in  $\text{HNO}_3$ .

**OPT. PROP.** Color copper red, often modified by alteration; streak copper red and shining metallic. Opaque. Refractive index  $N = 0.64$  Na. In vertically reflected light, pale pink. Percentage reflections:<sup>3</sup> red 89, orange 83, green 61.

**ALTER.** Copper oxidizes easily to cuprite or changes to malachite or azurite.

**OCCUR.** It is found in veins in all kinds of rocks, and in amygdaloidal cavities in basaltic rocks commonly associated with calcite, zeolites, etc. Also found rarely in sediments, especially sandstones. A large deposit of native copper is near Houghton, Michigan; it is also found at Broken Hill, New South Wales; Corocoro, Bolivia; Cananea, Mexico; etc.

<sup>3</sup> H. Schneiderhöhn and P. Ramdohr: *Lehrb. Erzmikr.*, II (1931).

<sup>4</sup> E. A. Owen and J. Iball: *Phil. Mag.*, XIII, 1020 (1932).

## IRON

## ISOMETRIC HEXOCTAHEDRAL

Fe

COMP. Native iron commonly contains 2-7% Ni with minor Co, Cu, C, S, etc.  
 STRUC.<sup>5</sup> Space group  $Im\bar{3}m$ ;  $a$  2.861 Å. U.C. 2.

PHYS. CHAR. Usually massive; cubic or octahedral crystals rare. Distinct cubic cleavage. Parting on 112. Malleable.  $H. = 4$ .  $G. = 7.3-7.87$ . Fuses at  $1535^{\circ}\text{C}$ . (pure Fe) after inversion at about  $785^{\circ}\text{C}$ . Soluble in HCl. Strongly magnetic.

OPT. PROP. Color steel gray to iron black. Luster metallic.  $N = 2.36$  (Drude); 1.73 (Kundt). The polished surface is white in reflected light; percentage reflections: <sup>3</sup> red 58, orange 59, green 64.

INVER. Low-temperature  $\alpha$ -iron inverts at about  $785^{\circ}\text{C}$ . to  $\gamma$ -iron, which is hexoctahedral, but it belongs to the face-centered space-group,  $Fm\bar{3}m$ , with  $a = 3.590$  Å; it may contain 25-75% Ni. It has no cleavage;  $H. = 5$ .  $G. = 7.8-8.2$ . Strongly magnetic.

ALTER. Alters easily to limonite when exposed to air.

OCCUR. Native iron is rare, but both  $\alpha$ -iron and  $\gamma$ -iron have been found in the earth's surface materials as well as in meteorites. Large masses are found at Disco, Greenland, in basalt.  $\alpha$ -Iron of meteorites is known as kamacite.  $\gamma$ -Iron is usually rich in nickel (and so may be called nickel-iron); it has been found in placers; in meteorites it is called *taenite*.

## SELENIUM

## TRIGONAL TRAPEZOHEDRAL

 $c/a = 1.136$ 

Se

STRUC.<sup>6</sup> Space group  $C3_12$  or  $C3_22$ ;  $a$  4.35,  $c$  4.95 Å. U.C. 3.

PHYS. CHAR. Acicular flexible crystals or clusters with good 01 $\bar{1}$ 2 cleavage.  $H. = 2$ .  $G. = 4.8$ . M.P.  $220^{\circ}\text{C}$ .

OPT. PROP. Color gray; luster metallic; streak red. Transparent only in very thin flakes. Uniaxial positive <sup>7</sup> with  $N_O = 3.00$  Na,  $N_E = 4.04$ ,  $N_E - N_O = 1.04$ . Polished surfaces reflect light well and are pleochroic with  $O =$  light creamy white,  $E =$  darker.

INVER. Two monoclinic phases are known: one is orange-red with  $a:b:c = 1.635:1:1.610$ ,  $\beta = 104^{\circ}2'$ , and  $G. = 4.47$ ; another is dark red with  $a:b:c = 1.592:1:1.135$ ,  $\beta = 93^{\circ}4'$ .

OCCUR. Found at Jerome, Arizona. It is recovered from flue dust in making  $\text{H}_2\text{SO}_4$ .

Mixtures of fused Se and S are useful immersion media. Indices are given in the following table.<sup>8</sup>

% Se	100	90	80	70	60	50	40	30	20	10	0
% S	0	10	20	30	40	50	60	70	80	90	100
N (Li)	2.716	2.53	2.40	2.30	2.22	2.16	2.11	2.07	2.03	2.00	1.978
N (Na)	2.92	2.67	2.49	2.37	2.27	2.20	2.15	2.10	2.06	2.025	1.998
N (Tl)				2.43	2.32	2.25	2.19	2.13	2.09	2.05	2.018

<sup>5</sup> E. A. Owen and E. L. Yates: *Phil. Mag.*, XV, 472 (1933).

<sup>6</sup> M. Straumanis: *Zeit. Krist.*, CII, 432 (1940).

<sup>7</sup> C. H. Skinner: *Phys. Rev.*, IX, 148 (1917).

<sup>8</sup> H. E. Merwin and E. S. Larsen: *Am. Jour. Sci.*, CLXXXIV, 42 (1912).

**MOISSANITE**<sup>9</sup> DIHEXAGONAL PYRAMIDAL  $c/a = 4.906$  SiC

**STRUC.**<sup>10</sup> Space group  $C6mc$ ;  $a$  3.073,  $c$  15.079 Å. U.C. 6.

**PHYS. CHAR.** Crystals thin basal plates with rare twinning on  $10\bar{1}4$  and poor basal cleavage.  $H. = 9.5$ .  $G. = 3.218$ .<sup>10</sup>

**OPT. PROP.** Uniaxial positive with extremely high refringence, strong birefringence, and very strong dispersion, as follows:<sup>10</sup>

$\lambda = 656$ (C)	589 (D)	486 (F)	Dispersion (F - C)
$N_E = 2.6696-2.6697$	$2.6889-2.6930$	$2.7405-2.7416$	$0.0815 \pm$
$N_O = 2.6284-2.6308$	$2.6467-2.6487$	$2.6919-2.6943$	$0.0635 \pm$
$N_E - N_O = 0.0412-0.0389$	$0.0422-0.0443$	$0.0486-0.0473$	$0.018 \pm$

Luster metallic. Color green to black; rarely bluish, red. Weakly pleochroic with O = olive green, E = greenish blue; again O = light blue, E = deep indigo blue. Some crystals show  $O > E$ ; others  $O < E$ . Surface films of silicon, often present, produce iridescent colors.

**INVER.** SiC crystals may have isometric or hexagonal or rhombohedral symmetry; accordingly three crystal phases may be recognized, namely,  $\alpha$ -SiC which is rhombohedral,  $\beta$ -SiC which is isometric, and  $\gamma$ -SiC which is hexagonal. Furthermore at least two types of the hexagonal phase are known as well as five of the rhombohedral phase! Still other types are probable.<sup>11</sup> One hexagonal type is described above; another type is also dihexagonal pyramidal, but  $c/a = 3.271$ ; its other properties are like those given above.  $\beta$ -SiC is isometric hextetrahedral<sup>10</sup> (probably the low-temperature phase); its space group is  $F\bar{4}3m$ ;  $a$  4.349 Å; U.C. 4.  $G. = 3.216$ . Isotropic with  $N = 2.63$  Li.  $\alpha$ -SiC is ditrigonal pyramidal; space group  $R3m$ . All the rhombohedral types have optic properties indistinguishable from those of the hexagonal phase. They all have  $a$  3.073 Å, but  $c$  varies; it is 12.267 Å in one type, in which  $a:c = 1:3.992$ ; in a second type  $c$  is 17.174 Å and  $a:c = 1:5.589$ ; in a third type  $c$  is 26.99 Å and  $a:c = 1:8.451$ ; in a fourth type  $c$  is 128.18 Å and  $a:c = 1:41.71$ ; and in a fifth type  $c$  is 218.657 Å and  $a:c = 1:71.12$  with U.C. 87. This variation in the value of  $c$  is due to a variation in the number of horizontal layers in the unit cell; this number is 15 in type 1, 21 in type 2, 33 in type 3, 51 in type 4, and 87 in type 5.

**OCCUR.** Found by Moissan in the Cañon Diablo meteorite; also reported in sediments. It is an important product of the electric furnace.

**DIAG.** Readily recognized by extreme hardness, extreme refringence, and extreme dispersion. Iridescent colors are usually present.

## 2. Elements with homopolar bonding

**DIAMOND** ISOMETRIC HEXOCTAHEDRAL (OR HEXTETRAHEDRAL?) C

**STRUC.**<sup>12</sup> Space group  $Fd3m$ ;  $a$  3.5595 Å. U.C. 8.

**PHYS. CHAR.** Crystals commonly octahedrons, dodecahedrons; also cubes, tetrahedrons and modified forms; faces usually curved and often

<sup>9</sup> Moissanite is obviously a carbide, but it is conveniently included here because it has metallic bonds between its atoms.

<sup>10</sup> N. W. Thibault: *Am. Mineral.*, XXIX, 327 (1944); XXXI, 512 (1946).

<sup>11</sup> L. S. Ramsdell: *Am. Mineral.*, XXXII, 64 (1947).

<sup>12</sup> W. Ehrenberg: *Zeit. Krist.*, LXIII, 320 (1926). Also  $F\bar{4}3m$ ; see C. V. Raman and S. Ramaseshan: *Proc. Ind. Acad. Sci.*, XXIV, A (1946).

striated. Twinning on 111 common, both contact and penetration types; also on 001. Perfect 111 cleavage.  $H. = 10$ .  $G. = 3.51(-3.2)$ . Infusible. Insoluble in acids and alkalis. Diamond has the greatest hardness and the lowest compressibility known. The hardness of diamond varies much with variations in direction in a crystal.<sup>13</sup>

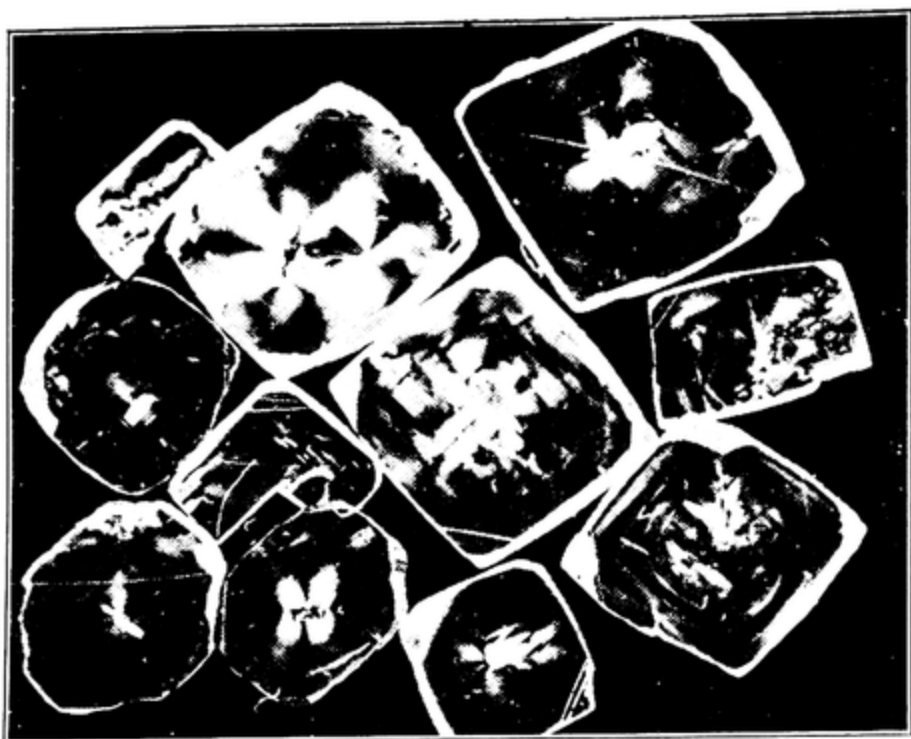


FIG. 17. Photomicrograph of 100 slices of diamonds between crossed nicols.  $\times 3.5$ . Supplied through courtesy of Hamilton Watch Co. and U. S. Industrial Diamond Corp.

OPT. PROP. Usually weakly anisotropic, probably due to strain with birefringence perceptible only in thick plates (see Fig. 17); rarely distinctly uniaxial. Dispersion very strong.

$$N = 2.4135 \text{ Li, } 2.4195 \text{ Na, } 2.4278 \text{ Tl}$$

Colorless, white, yellow, orange, red, green, blue, brown, black. In thin section colorless and transparent to nearly opaque, but not pleochroic. Luster adamantine (to greasy).

INVER. Inverts to another form<sup>14</sup> at about  $1885^{\circ} \text{ C}$ .

INCL. Inclusions are gaseous or solid; often carbonaceous and abundant, thus giving color.

<sup>13</sup> H. Winchell: *Am. Mineral.*, XXXI, 149 (1946).

<sup>14</sup> G. Friedel and G. Ribaut: *Bull. Soc. Fr. Min.*, XLVII, 94 (1924).



**OCCUR.** In alluvial deposits associated with heavy minerals; also in quartz conglomerate, in itacolumite, and in a peculiar peridotite called kimberlite, as in South Africa and Arkansas. Also reported in a few meteorites.

**DIAG.** The hardness, adamantine luster, and insolubility are quite distinctive. Rarely found in thin sections, even of diamondiferous rocks, because not polished by ordinary processes.

### 3. Elements with residual bonding

**GRAPHITE**                      **DIHEXAGONAL DIPYRAMIDAL**                       $c/a = 2.752$                       **C**

**STRUC.** Space group <sup>16</sup>  $C6/mmc(?)$ ;  $a$  2.47,  $c$  6.79 Å. U.C. 4.

**PHYS. CHAR.** Crystals rounded hexagonal lamellae; usually found in concentric foliated masses. Perfect basal cleavage; the laminae are flexible and not elastic.  $H. = 1-2$ . Greasy feel.  $G. = 2.15-2.25$ . Infusible; deflagrates with  $KNO_3$ . Insoluble.

**OPT. PROP.** Opaque in ordinary thin sections, but translucent to transparent and blue or greenish gray in very thin flakes. Uniaxial negative with  $N$  between <sup>16</sup> 1.98 and 2.03 Li. In reflected light <sup>3</sup> strongly pleochroic and birefringent. Reflection percentages for  $O$ : red 23, orange 23.5, green 22.5; for  $E$ : red 5.5, orange 5, green 5. Color and streak black.

**OCCUR.** Graphite is found in small amount in many igneous rocks; also in greater quantity in some schists and gneisses. It is also found in contact rocks, in beds of coal that have been metamorphosed, and in meteorites. It is mined in Ceylon and Madagascar, and at Granville, Quebec, Ticonderoga, New York, etc.

**ALTER.** Changes to graphitic acid (when treated with  $HNO_3$  and  $KClO_3$ ), which has nearly the same optic properties, and is pleochroic with  $O =$  dark green and  $E =$  almost colorless. On heating it changes back to graphite.

**DIAG.** Graphite deflagrates in a platinum spoon with niter, producing potassium carbonate. Molybdenite resembles graphite in external characters, but it is fusible, giving sulfur coatings; also it does not deflagrate, and it has a streak on smooth porcelain which is slightly greenish instead of black.

**SULFUR**                                      **ORTHORHOMBIC DIPYRAMIDAL**                                      **S**  
 $a:b:c = 0.813:1:1.903$

**STRUC.**<sup>17</sup> Space group  $Fddd$ ;  $a$  10.48,  $b$  12.92,  $c$  24.55 Å. U.C. 128 (= 16  $S_8$  molecules).

**PHYS. CHAR.** Crystals usually dipyramidal; also thick tabular or modified. Twinning on 101, 110, or 011, rare.  $H. = 2$ .  $G. = 2.04$ . M.P. 112.8° C. Burns at 270° C. B.P. 444.6° C. Insoluble in acids; soluble in  $CS_2$ .

**OPT. PROP.** Color yellow, rarely brownish, reddish, or gray; streak white. Luster resinous to greasy. The optic plane is 010;  $Z = c$ . See Figs. 18 and 19.  $(+ )2V = 68^\circ 58'$  Na,  $r < v$  weak.  $N_X = 1.9398$  Li, 1.9579 Na, 1.9764 Tl,  $N_Y$

<sup>16</sup> C. Palache: *Am. Mineral.*, XXVI, 709 (1941).

<sup>16</sup> P. P. Pilipenko and I. I. Oreshkin: *Min. Abst.*, VII, 211 (1938).

<sup>17</sup> B. E. Warren and J. T. Burwell: *J. Chem. Phys.*, III, 6 (1935).



$= 2.0171 \text{ Li}, 2.0377 \text{ Na}, 2.0586 \text{ Tl}, N_z = 2.2158 \text{ Li}, 2.2452 \text{ Na}, 2.2754 \text{ Tl}, N_z - N_x = 0.2873 \text{ Na}.$

**INVER.** Orthorhombic sulfur inverts to a monoclinic phase called  $\beta$ -sulfur at  $98^\circ \text{ C}.$  This phase has  $a:b:c = 0.9958:1:0.9998, \beta = 95^\circ 46'.$  Crystals prismatic with distinct 001 and 110 cleavages; twinning on 011, 012, 100.  $H. = 1.5.$   $G. = 1.96.$   $F. = 119^\circ \text{ C}.$  Color light honey-yellow, or brownish due to organic matter. The optic plane is 010;  $X' \wedge c$  on 110  $= 44^\circ$  (Gaubert).  $(- )2V = 58^\circ \pm.$   $N = 1.96$  (calc.)  $N_z - N_x = \text{weak}.$  Easily crystallized from fusion or from solu-

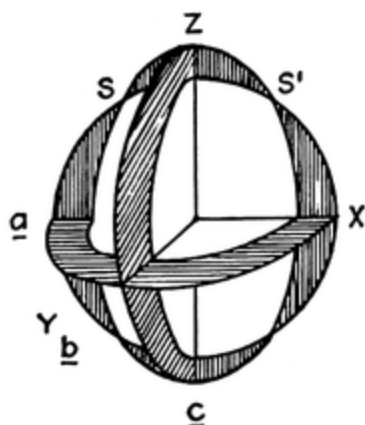


FIG. 18. Wave fronts in axial planes in sulfur, differences of velocities being exaggerated.

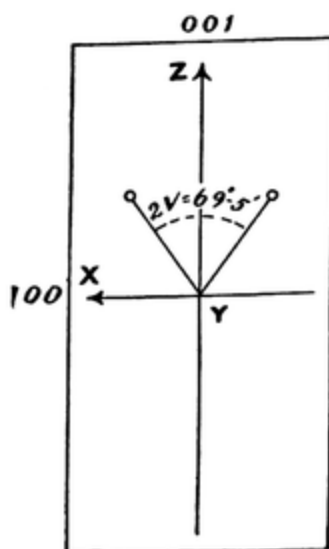


FIG. 19. The optic orientation of sulfur.

tion; a metastable phase rare in nature. Another monoclinic phase, called  $\gamma$ -sulfur or *rosickyite*,<sup>18</sup> has  $a:b:c = 1.061:1:0.709, \beta = 91^\circ 48'.$  Crystals nearly equant or {010} plates or rarely acicular. No cleavage.  $H.$  low.  $G. < 2.07.$  Color light yellow. The optic plane is 010;  $X \wedge c = +1\frac{1}{4}^\circ \pm.$  Refrindex and birefringence strong. Very rare in nature; produced in concretions by alteration of pyrite. Three other crystal phases are known but have not been found in nature. One is rhombohedral and uniaxial negative<sup>19</sup> with  $G. = 2.135.$

**ALTER.** Sulfur oxidizes slowly to sulfurous and sulfuric acids, which yield sulfates.

**OCCUR.** Found especially about volcanoes, as at the Solfatara in Italy, and in gypsum deposits, as in Sicily and Louisiana; less abundant in coal deposits, veins, etc., as a result of reduction of sulfides or sulfates. Deposited by some hot springs, as in Yellowstone Park.

<sup>18</sup> J. Sekanina: *Zeit. Krist.*, LXXX, 174 (1931).

<sup>19</sup> C. Friedel: *C. R. Acad. Sci. Paris*, CXII, 834 (1891).

## II. HALIDES

The halides are classified as simple halides and multiple halides, oxyhalides and hydrated halides being included. The arrangement is in order of the decreasing A to X (or A + B to X) ratio in the formulas. A represents one or two (or even more) metals having atoms of such size as can replace each other to form one equipoint set. B represents one (or more) other metals having atoms of another size. X stands for any halogen element, and also for oxygen or hydroxyl.

An outline classification of halides follows:

### A. Simple halides.

1. Simple halides with type formula AX.
2. Simple halides with type formula  $AX_2$ .
3. Simple halides with type formula  $AX_3$ .
4. Simple oxyhalides.

### B. Multiple halides.

1. Multiple halides with type formula  $A_mB_nX_p$  and  $(m+n):p > 1:2$ .
2. Multiple halides with type formula  $A_mB_nX_p$  and  $(m+n):p = 1:2$ .
3. Multiple halides with type formula  $A_mB_nX_p$  and  $(m+n):p < 1:2$ .
4. Multiple oxyhalides.

## A. SIMPLE HALIDES

### 1. Simple halides with type formula AX

#### HALITE

#### ISOMETRIC HEXOCTAHEDRAL

#### NaCl

**STRUC.** Space group  $^1 Fm\bar{3}m$ ;  $a$  5.628 Å; U.C. 4. The arrangement of the atoms is shown in Fig. 20.

**PHYS. CHAR.** Crystals usually cubic with perfect cubic cleavage. Percussion figure on {100} with rays parallel to the binary axes of symmetry.  $H. = 2.5$ .  $G. = 2.17$ . Easily fusible (at 802° C.), often with

<sup>1</sup> M. Straumanis and A. Jevins: *Zeit. Phys.*, CII, 353 (1936).

decrepitation. Soluble in  $H_2O$ ; taste salty. Gives an intensely yellow flame.

**OPT. PROP.** Usually isotropic, but may be slightly anisotropic. Refrindex low;  $N = 1.5443 D$ ;  $N_F - N_C = 0.0127$ . Colorless or white, with vitreous luster; impurities may produce red, yellow, blue, gray, or black color.

**INCL.** Inclusions of gypsum, anhydrite, limonite, shale, etc., are common. Further, liquid inclusions often in "negative crystals" are not rare; they may contain gas bubbles, sometimes movable.

**OCCUR.** Found chiefly in sedimentary deposits formed by evaporation in estuaries or salt lakes. Occurs in rocks of various ages associated with gypsum, anhydrite, polyhalite, carnallite, glauberite, etc. Found rarely about volcanoes.

**Sylvite** (KCl) is isometric hexoctahedral; space group<sup>2</sup>  $Fm\bar{3}m$ ;  $a$  6.278 Å; U.C. 4; cubic cleavage.  $H. = 2$ .  $G. = 1.99$ . Fuses with violet flame color. Soluble in  $H_2O$ ; taste salty. Isotropic with  $N = 1.4904 D$ ;  $N_F - N_C = 0.0112$ . Colorless, white, or tinted by inclusions. Found in salt-lake deposits with halite and carnallite; also formed about volcanoes.

NaCl and KCl do not intercrystallize in all proportions<sup>3</sup> but form a series of double salts which are stable at the temperature of formation but unstable at ordinary temperature, breaking down into simple halides. The breakdown is submicroscopic and causes the measured index of the (microscopically uniform) aggregate to be the additive index of intimate mixtures of NaCl and KCl in the given proportions. Accordingly the tenor of Na and K in any mixture of these chlorides may be determined quantitatively by measuring the index of refraction. All the double salts have perfect cubic cleavage and the following indices:

Salt	N (D)	Salt	N (D)
NaCl	1.544	4NaCl·3KCl	1.518
7NaCl·KCl	1.536	NaCl·KCl	1.514
5NaCl·KCl	1.533	2NaCl·3KCl	1.5085
3NaCl·KCl	1.528	2NaCl·5KCl	1.503
2NaCl·KCl	1.523	2NaCl·7KCl	1.500
3NaCl·2KCl	1.519	KCl	1.490

**Villiaumite** (NaF) is isometric;  $a$ <sup>4</sup> 4.615 Å; cubic cleavage.  $H. = 3.5$ .  $G. = 2.79$ . Fuses at 986° C. Soluble in hot water. Very weak negative birefringence at ordinary temperature with X normal to 001. Refrindex also negative ( $N = 1.3258$ ) producing marked relief.  $N_F - N_C = 0.0039$ . Except when heated

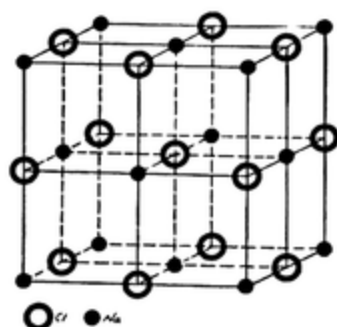


FIG. 20. The atomic structure of halite.

<sup>2</sup> T. Yuching: *Phys. Rev.*, XL, 662 (1932).

<sup>3</sup> C. B. Slawson: *Am. Mineral.*, XIV, 293 (1929).

<sup>4</sup> T. Barth and G. Lunde: *Cent. Min. Geol.*, 1927A, 57.

it is colored red to violet and is pleochroic with  $X$  = golden yellow and  $Z$  = carmine red. Found in nepheline syenite in French Guiana.

**Salammoniac** ( $\text{NH}_4\text{Cl}$ ) is isometric hexoctahedral;  $a$  3.86 Å; twinning on 111.  $H. = 1.52$ .  $G. = 1.528$ . Soluble in  $\text{H}_2\text{O}$ . Sublimes without fusion. Isotropic with  $N = 1.6380$  C, 1.6426 D, 1.6529 F (Grailich);  $N = 1.639$  D (Merwin<sup>5</sup>). Color white, yellowish, grayish. Inverts (reversibly) at 156° C. from CsCl to NaCl space lattice; then  $a = 6.53$  and  $G. = 1.27$ . Found about volcanoes as at Vesuvius, near ignited coal seams as at St. Etienne, France, and in guano.

**Nantokite** ( $\text{CuCl}$ ) has {110} cleavage;  $a$  5.41 Å.  $H. = 2 - 2.5$ .  $G. = 3.93$ . Oxidizes readily in moist air. Soluble in  $\text{H}_2\text{O}$ . Isotropic with  $N = 1.955$  C, 1.973 D, 1.996 Tl (Haase); 1.930 (Larsen). Colorless. Found at Carmen Bajo, Chile, and Broken Hill mines, New South Wales.

**Marshite** ( $\text{CuI}$ ) is isometric hextetrahedral with dodecahedral cleavage;  $a$  6.05 Å. U.C. 4.  $H. = 2.5$ .  $G. = 5.68$ .  $F. = 1.5(?)$ . Isotropic with  $N = 2.313$  C, 2.346 D, 2.385 Tl, the dispersion being greater than that of diamond. Color oil brown, pale yellow to brick red; streak bright lemon yellow. Becomes dark red and birefringent on heating. Found at the Broken Hill mines, New South Wales, and at Chuquicamata, Chile.

**Miersite** ( $4\text{AgI} \cdot \text{CuI}$ ), described as a definite compound, may be only an example of part of a  $\text{CuI-AgI}$  series. It has the same form and cleavage as marshite with  $H. = 2$ ,  $G. = 5.64$ , and  $N = 2.20$ . Color yellow.

#### CERARGYRITE (*Horn Silver*) ISOMETRIC HEXOCTAHEDRAL

$\text{Ag}(\text{Cl}, \text{Br}, \text{I})$

**COMP.** Cerargyrite forms a continuous series from  $\text{AgCl}$  (*chlorargyrite*) through  $\text{Ag}(\text{Cl}, \text{Br})$  (*embolite*) to  $\text{AgBr}$  (*bromargyrite*); further a limited tenor of  $\text{I}$  may be present as in  $\text{Ag}(\text{Cl}, \text{Br}, \text{I})$  (*iodembolite*); it may also contain some mercury.

**STRUC.** Space group  $^6 Fm\bar{3}m$ ;  $a$  5.54 Å ( $\text{AgCl}$ ), 5.76 ( $\text{AgBr}$ ); U.C. 4.

**PHYS. CHAR.** Crystals usually cubic; no cleavage; twinning on 111: usually massive, encrusting.  $H. = 1-1.5$  ( $\text{AgCl}$ ) to 2-3 ( $\text{AgBr}$ ).  $G. = 5.55$  ( $\text{AgCl}$ ) to 6.245 ( $\text{AgBr}$ ). See Fig. 21. Soluble in  $\text{NH}_4\text{OH}$ . Sectile. Fuses at 452° C. ( $\text{AgCl}$ ), 412° C.

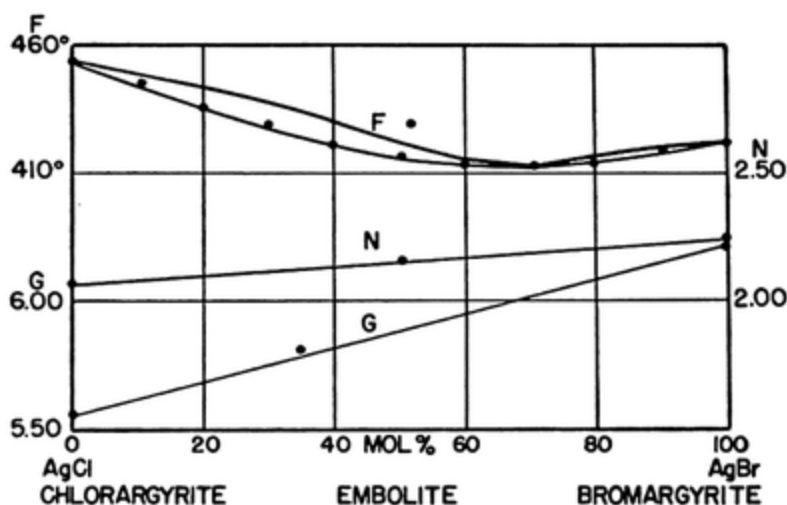


FIG. 21. Properties of cerargyrite.

<sup>4</sup> R. W. G. Wyckoff: *Am. Jour. Sci.*, CCIV, 470 (1922).

<sup>5</sup> T. Barth and G. Lunde: *Norsk Geol. Tidssk.*, VIII, 281 (1925).

<sup>7</sup> O. W. Jarrell: *Am. Mineral.*, XXIV, 629 (1939).

{Ag(Cl,Br)}, 422° C. (AgBr). See Fig. 21. Isotropic with very high refringence as follows: for AgCl,  $N = 2.044$  C, 2.059 D, 2.095 F,  $N_F - N_C = 0.05$ ; for AgBr,  $N = 2.232$  C, 2.252 D, 2.312 F,  $N_F - N_C = 0.08$ . See Fig. 21. Color of chlorargyrite pearl gray, grayish green, or white, becoming violet in sunlight; color of embolite gray to yellow or yellowish green, becoming dark in sunlight; color of iodembolite sulfur yellow, sometimes greenish; color of bromargyrite yellow, amber, slightly greenish, with little change in sunlight.

**OCCUR.** Found in the oxide zone of silver deposits, often with ores of lead, copper, etc., as at Atacama, Chile; Freiberg, Germany; Austin, Nevada, etc.

**Calomel** ( $Hg_2Cl_2$ ) is ditetragonal dipyramidal with  $c/a = 2.436$ ; space group  $I4/mmm$ ;  $a$  4.47,  $c$  10.89 Å; U.C. 4. Crystals pyramidal, or basal plates, often highly complex; distinct 110 cleavage.  $H. = 1-2$ .  $G. = 6.48$ . Infusible but volatile. Soluble in aqua regia. Uniaxial positive. Refringence very high; birefringence twice as strong as in any other known mineral except stibnite.  $N_O = 1.973$ ,  $N_E = 2.656$ ,  $N_E - N_O = 0.683$ . For  $N_O$ :  $N_F - N_C = 0.057 \pm$ . Color white, yellowish, grayish, brown. Found in the oxide zone of the ore deposits, as at Almaden, Spain.

**IODYRITE**                      DIHEXAGONAL PYRAMIDAL                       $c/a = 1.64$                       AgI

**STRUC.**<sup>9</sup> Space group:  $C6mm$ ,  $C6cc$ ,  $C6cm$ , or  $C6mc$ ,  $a$  4.59,  $c$  7.53 Å. U.C. 2.

**PHYS. CHAR.** Crystals prismatic with rare twinning on  $30\bar{3}2$ . Also massive and lamellar. Perfect basal cleavage; laminae flexible; soft; sectile.  $G. = 5.6$ . Fuses at 527° C. giving fumes of I and Ag globules. Soluble in  $NH_4OH$ .

**OPT. PROP.** Uniaxial positive with  $N_O = 2.153$  C, 2.182 D, 2.279 F (Wernicke<sup>10</sup>);  $N_O = 2.21$ ,  $N_E = 2.22$ ,  $N_E - N_O = 0.01$ . For  $N_O$ :  $N_F - N_C = 0.126$  (Larsen<sup>11</sup>). May be slightly biaxial. Abnormal green interference colors. Color yellow to yellowish green; sometimes brownish. Streak yellow.

**INVER.** A reversible inversion to an isometric form with  $a$  6.49 Å occurs sharply at 146° C.

**OCCUR.** Found in veins in silver mines, as at Lake Valley, New Mexico.

## 2. Simple halides with type formula $AX_2$

**FLUORITE**                      ISOMETRIC HEXOCTAHEDRAL                       $CaF_2$

**COMP.** Fluorite is nearly always quite pure  $CaF_2$ , but in rare cases it may take into crystal solution up to 50%  $YF_3$  (then called *ytthrofluorite*) or up to 55%  $CeF_3$  (then called *cerfluorite*—unknown in nature): mix-crystals of ytthrofluorite and cerfluorite are called *ytthrocerite*.

**STRUC.**<sup>12</sup> Space group  $Fm3m$ ;  $a$  5.45 Å (5.49 with 15%  $YF_3$ ); U.C. 4. See Fig. 22.

<sup>8</sup> R. J. Havighurst: *Am. Jour. Sci.*, CCX, 15 (1925).

<sup>9</sup> G. Aminoff: *Zeit. Krist.*, LVII, 180 (1922); *Geol. För. Förh.*, XLIV, 444 (1922).

<sup>10</sup> W. Wernicke: *Pogg. Ann.*, CXLII, 571 (1871).

<sup>11</sup> E. S. Larsen: *U. S. Geol. Surv. Bull.* 679 (1921) and 848 (1934).

<sup>12</sup> V. M. Goldschmidt: *Strukturber.*, I (1931).

**PHYS. CHAR.** Crystals usually cubic; sometimes octahedral or dodecahedral. Twinning common on 111, usually with interpenetration. See Figs. 23 and 24. Perfect octahedral cleavage, imperfect in yttrifluorite.  $H. = 4$  (4.5 for yttrifluorite);  $G. = 3.18$  (up to 3.55 for yttrifluorite). Fusible with red flame color. Soluble in  $H_2SO_4$  with evolution of  $HF$ .

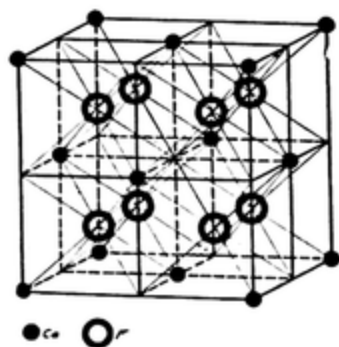


FIG. 22. The atomic structure of fluorite.

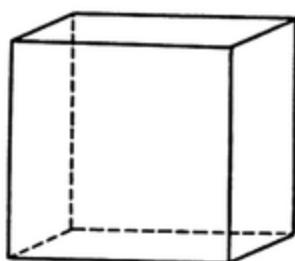


FIG. 23. A crystal form of fluorite.



FIG. 24. A penetration twin of fluorite.

**OPT. PROP.** Isotropic with refractive index so low that the negative relief is marked. May show abnormal birefringence. For ordinary  $CaF_2$ :  $N = 1.43385$  Na (remarkably constant<sup>13</sup>),  $N_F - N_C = 0.00454$ .  $N$  decreases 0.00001 for  $1^\circ C.$  rise in temperature.

With 10%  $YF_3$  and 1%  $CeF_3$ :  $N = 1.4425$ ,  $G. = 3.32$ ; with 16.8%  $(Y,Ce)F_3$ :  $N = 1.4483$ ,  $G. = 3.41$ ; with 13%  $YF_3$ :  $N = 1.455$ ,  $G. = 3.55$ ,  $H. = 4.5$ . Fluorite may be colorless, white, or brightly tinted yellow, blue, purple, green, red, or brown with the color not uniformly distributed. Color of yttrifluorite yellow to brown or green; color fades on exposure to light. Color of yttrocerite violet or blue, uneven. The cause of the color is not certainly known; it may be due to small quantities of oxides of iron or manganese, or to dispersed calcium or fluorine or hydrocarbons.

**OCCUR.** Fluorite is rarely found in igneous rocks as a primary constituent; in certain cases it seems to have been formed through the action of fumaroles. It is common in veins associated with quartz and barite, and sometimes with ores. It also occurs in some sedimentary and metamorphic rocks. Yttrifluorite and yttrocerite are very rare; found in some pegmatites.

**DIAG.** Fluorite is characterized by its crystal form, octahedral cleavage, very low refringence, vitreous luster, softness, and ready fusibility. Color, when present, is not uniformly distributed.

<sup>13</sup> H. E. Merwin: *Am. Jour. Sci.*, CLXXXII, 429 (1911).



**Sellaite** ( $MgF_2$ ) is ditetragonal dipyramidal with  $c/a = 0.66$ . Space group <sup>14</sup>  $P4/mnm$ ;  $a$  4.66,  $c$  3.078 Å; U.C. 2. Crystals usually prismatic with perfect 100 and 110 cleavages.  $H. = 5$ .  $G. = 3.17$ . Fusible with intumescence at  $1221^\circ C$ . Soluble in pure  $H_2SO_4$ . Uniaxial positive with  $N_O = 1.3780$ ,  $N_E = 1.3897$ ,  $N_E - N_O = 0.0117$ . Colorless. Found in anhydrite or sulfur; also with fluorite. Differs from scapolite by its easy cleavages and its optic sign.

**Matlockite** ( $PbFCl$ ) is ditetragonal dipyramidal with  $c/a = 1.763$ . Space group <sup>15,16</sup>  $Pnmm$ ;  $a$  4.09,  $c$  7.21 Å; U.C. 2. Crystals basal tablets with perfect basal cleavage.  $H. = 3$ .  $G. = 7.2$ .  $F. = 1$ . Soluble in  $HNO_3$ . Uniaxial negative; <sup>16</sup> for  $\lambda = 656$ :  $N_O = 2.127$ ,  $N_E = 1.994$ ,  $N_O - N_E = 0.133$ ; for  $\lambda = 589$ :  $N_O = 2.145$ ,  $N_E = 2.006$ ,  $N_O - N_E = 0.139$ ; for  $\lambda = 486$ :  $N_O = 2.191$ ,  $N_E = 2.039$ ,  $N_O - N_E = 0.152$ ; for  $N_O$ :  $N_F - N_C = 0.074$ . Some crystals are biaxial negative with  $2E = 55^\circ$  ca.  $r < v$ , the optic plane being 010. Color yellow or greenish. Found at lead mines; as at Crawford near Matlock, England; also at Vesuvius.

**Chloromagnesite** ( $MgCl_2$ ) is hexagonal scalenohedral with  $c/a = 2.45$ . Space group  $R3m$ ;  $a$  7.18,  $c$  17.60 Å. Hexagonal U.C. 16. Soft. Very deliquescent.  $F. = 1$ . Uniaxial negative with  $N_O = 1.675$ ,  $N_E = 1.59$ ,  $N_O - N_E = 0.085$  ca. Colorless. Found about volcanoes, as at Vesuvius.

**Penfieldite** [ $Pb_4Cl_6(OH)_2$ ] is hexagonal <sup>16a</sup> with  $c/a = 0.785$ . Crystals prismatic with distinct basal cleavage.  $G. = 6.6$ .  $F. = 1$ . Soluble in  $HNO_3$ . Uniaxial positive with  $N_O = 2.13$ ,  $N_E = 2.21$ ,  $N_E - N_O = 0.08$ . Color white. Found in lead slags at Laurium, Greece; also in Chile.

**Lawrencite** ( $FeCl_2$ ) is hexagonal scalenohedral with  $c/a = 2.45$ . Space group  $R3m$ ;  $a$  7.15,  $c$  17.52 Å. Uniaxial negative with <sup>17</sup>  $N_O = 1.567$ ,  $N_O - N_E =$  weak (Larsen). Color green to brown; unstable. Found in meteorites, and, rarely, about volcanoes.

**Hydrophilite** ( $CaCl_2$ ) is orthorhombic with  $a:b:c = 0.971:1:0.653$ . Space group <sup>18</sup>  $Pnnm(?)$ ;  $a$  6.24,  $b$  6.43,  $c$  4.20 Å. U.C. 2. Perfect prismatic cleavage; lamellar twinning on 110 like that of microcline. Very deliquescent and hygroscopic.  $(+2V =$  moderate,  $N_X = 1.600$ ,  $N_Y = 1.605$ ,  $N_Z = 1.613$ ,  $N_Z - N_X = 0.013$ . May react with index liquids to an isotropic substance with  $N = 1.52$ ; does not react with  $\alpha$ -monobromonaphthalene or with paraffin oil. Rare about volcanoes.

**Cotunnite** ( $PbCl_2$ ) is orthorhombic dipyramidal with  $a:b:c = 0.595:1:1.187$ . Space group  $Pnmb$ ;  $a$  4.52,  $b$  7.61,  $c$  9.03 Å. U.C. 4. Crystals tabular parallel to 010; also acicular parallel to  $a$ . Perfect 001 cleavage. Soft.  $G. = 5.84$ .  $F. = 1$ . Soluble in hot water. Optic plane is 010;  $Z = c$ .  $(+2V = 67^\circ$  Na,  $N_X = 2.199$  Na,  $N_Y = 2.217$ ,  $N_Z = 2.260$ ,  $N_Z - N_X = 0.061$ . Color white, greenish, yellowish. Rare about volcanoes.

<sup>14</sup> H. E. Buckley and W. S. Vernon: *Phil. Mag.*, XLIX, 945 (1925).

<sup>15</sup> W. Nieuwenkamp: *Zeit. Krist.*, LXXXVI, 470 (1933).

<sup>16</sup> F. A. Bannister and M. H. Hey: *Mineral. Mag.*, XXIII, 587 (1934).

<sup>16a</sup> S. G. Gordon: *Not. Nat. Acad. Nat. Sci. Phila.*, 69, 1941.

<sup>17</sup> Index too low as compared with  $MgCl_2$ . Perhaps hydrated? (A.N.W.) But even the hydrate ( $2H_2O$ ) has  $N_Y = 1.6435$ . See A. Neuhaus: *Zeit. Krist.*, XCVIII, 112 (1937).

<sup>18</sup> C. B. Slawson: *Am. Mineral.*, XIV, 160 (1929). P. Wulff (*Zeit. Krist.*, LXXVII, 84, 1931) gives  $N_X = 1.531$ ,  $N_Y = ?$ ,  $N_Z = 1.542$ .

**Laurionite**  $[\text{Pb}(\text{OH})\text{Cl}]$  is orthorhombic dipyramidal with  $a:b:c = 0.734:1:0.418$ . Space group <sup>19</sup>  $Pnam$ ;  $a$  7.1,  $b$  7,  $c$  4.05 Å, U.C. 4. Crystals prismatic with distinct 100 cleavage.  $H. = 3-3.5$ .  $G. = 6.24$ .  $F. = 1$ . Soluble in  $\text{HNO}_3$ . Loses water at  $142^\circ \text{C}$ . Optic plane <sup>20</sup> is 100;  $X = c$ .  $(-)\text{2V} = 82^\circ$ ;  $N_X = 2.077$ ,  $N_Y = 2.116$ ,  $N_Z = 2.158$  (Smith).<sup>21</sup> Colorless between parallel nicols at  $0^\circ$  and  $90^\circ$  but dark gray to bluish at  $45^\circ$ . Colorless in mass. Found in ancient lead slags at Laurium, Greece.

**ATACAMITE****ORTHORHOMBIC DIPYRAMIDAL**

$$a:b:c = 0.661:1:0.753$$

**STRUC.** Space group <sup>22</sup>  $Pnam$ ;  $a$  6.01,  $b$  9.13,  $c$  6.84 Å; U.C. 4.

**PHYS. CHAR.** Crystals prismatic, vertically striated, or tabular; also fibrous, or granular. Twinning on 110. Perfect 010 cleavage.  $H. = 3-3.5$ .  $G. = 3.78$ .  $F. = 3.5$ . Soluble in  $\text{HCl}$ .



FIG. 25. The optic orientation of atacamite.

**OPT. PROP.** The optic plane is 100;  $X = b$ . See Fig. 25.  $(-)\text{2V} = 75^\circ$ ,  $r < v$  strong;  $(2H = 94^\circ \text{Na}, 99^\circ \text{Ti})$ .  $N_X = 1.831$ ,  $N_Y = 1.861$ ,  $N_Z = 1.880$  Ti,  $N_Z - N_X = 0.049$  Ti. Color bright green; streak apple green. Weakly pleochroic with  $X =$  pale green,  $Y =$  yellowish green,  $Z =$  grass green.

**ALTER.** Changes rather easily to malachite or to chrysocolla.

**OCCUR.** Found in the oxide zone of copper deposits, as at Atacama, Chile, and Jerome, Arizona; also in sands, and about hot springs on brass or copper.

**DIAG.** Differs from malachite in having parallel extinction and weaker birefringence; the cleavage is parallel to the positive elongation and normal to the acute bisectrix  $X$ .

**Antofagastite**  $(\text{CuCl}_2 \cdot 2\text{H}_2\text{O})$  is orthorhombic dipyramidal with  $a:b:c = 0.918:1:0.462$ . Space group <sup>23</sup>  $Pbmn$ ;  $a$  7.38,  $b$  8.04,  $c$  3.72 Å. U.C. 2. Perfect 110 and good 001 cleavages.  $H. = 2.5$ .  $G. = 2.4$ . Soluble in  $\text{H}_2\text{O}$ .  $F. = 2$ . The optic plane is 001;  $Z = a$ .  $(+)\text{2V} = 75^\circ$ ,  $r < v$ .  $N_X = 1.646$ ,  $N_Y = 1.685$ ,  $N_Z = 1.745$ ,  $N_Z - N_X = 0.099$ . Color bluish green with  $X =$  bright green,  $Y =$  olive green,  $Z =$  pale blue. Found in gossan at Antofagasta, Chile.

**Bischofite**  $(\text{MgCl}_2 \cdot 6\text{H}_2\text{O})$  is monoclinic prismatic with  $a:b:c = 1.387:1:0.854$ ,  $\beta = 93^\circ 42'$ . Space group  $C2/m$ ;  $a$  9.90,  $b$  7.15,  $c$  6.10, U.C. 2. Crystals fibrous or granular.  $H. = 1.5$ .  $G. = 1.59$ . Fusible. Soluble in water. The optic plane and  $X$  are normal to 010;  $Y \wedge c = -9.5^\circ$ .  $(+)\text{2V} = 79^\circ$ ,  $r > v$ , weak. Crossed dispersion about  $X$  distinct.  $N_X = 1.495$ ,  $N_Y = 1.507$ ,  $N_Z = 1.528$ ,  $N_Z - N_X = 0.033$ . (Görgey<sup>24</sup>).  $N_X = 1.492$ ,  $N_Y = 1.506$ ,  $N_Z = 1.519$ ,  $N_Z - N_X = 0.027$  (Henderson<sup>25</sup>). Colorless. Found in salt deposits in Prussia, etc.

<sup>19</sup> S. Goldsztaub: *C. R.*, CCIV, 702 (1937) and CCVIII, 1234 (1939), H. Brasseur: *Min. Abst.*, IX, 225 (1946).

<sup>20</sup> C. Palache: *Mineral. Mag.*, XXIII, 573 (1934).

<sup>21</sup> G. F. H. Smith; *Mineral. Mag.*, XII, 102 (1899); confirmed by H. Berman: *Mineral. Mag.*, XXIII, 573 (1934).

<sup>22</sup> A. F. Wells: *Acta Cryst.*, II, 175 (1949).

<sup>23</sup> C. Palache and W. F. Foshag: *Am. Mineral.*, XXIII, 85 (1938).

<sup>24</sup> R. Görgey: *Tsch. Min. Pet. Mit.*, XXIX, 200 (1910).

<sup>25</sup> E. P. Henderson: *U. S. Geol. Surv. Bull.* 833, 80 (1932).



**Paralaurionite**  $[\text{Pb}(\text{OH})\text{Cl}]$  is monoclinic with  $a:b:c = 2.704:1:1.809$ ,  $\beta = 117^\circ 13'$ ; the stability relations with laurionite are unknown. Crystals tabular parallel to 100 or acicular parallel to  $b$ . Twinned on 100. Distinct basal cleavage.  $G. = 6.05$ .  $F. = 1$ . Soluble in  $\text{HNO}_3$ . Loses water at  $180^\circ \text{C}$ . The optic plane is 010;  $Z \wedge c = -25^\circ$ ; sections parallel to 100 show a double interference figure due to twinning.  $(- )2V = \text{medium to large}$ ;  $r < v$  strong.<sup>26</sup>  $N_X = 2.05$ ,  $N_Y = 2.15$ ,  $N_Z = 2.20$ ,  $N_Z - N_X = 0.15$ . Colorless to white, or violet (*rafaelite*) and pleochroic with  $Y = \text{deep violet}$ ,  $X$  and  $Z = \text{violet red to reddish yellow}$ ; the color may be very unequally distributed in zones parallel to crystal edges. Found in lead slags at Laurium, Greece, and also (*rafaelite*) at a lead mine in Chile.

**Fiedlerite**  $[\text{Pb}_3(\text{OH})_2\text{Cl}_4]$  is monoclinic with  $a:b:c = 1.024:1:0.899$ ,  $\beta = 102^\circ 30'$ . Crystals {100} tablets commonly twinned on 100. Distinct 100 cleavage.  $H. = 3$ .  $G. = 5.88$ . Soluble in  $\text{HNO}_3$ . The optic plane<sup>26</sup> and  $Z$  are normal to 010;  $Y \wedge c = +34^\circ$ .  $(- )2V = \text{large}$ ,  $r < v$  perceptible.  $N_X = 1.98$ ,  $N_Y = 2.04$ ,  $N_Z = 2.10$ ,  $N_Z - N_X = 0.12$ . Colorless. Found in lead slags at Laurium, Greece.

### 3. Simple halides with type formula $\text{AX}_3$

**Fluocerite**  $(\text{Ce}, \text{La}, \text{Di})\text{F}_3$  is hexagonal<sup>27</sup> with  $c/a = 1.374$ ; crystals prismatic or tabular. Perfect basal cleavage.  $H. = 4$ .  $G. = 5.7\text{--}6.1$ .  $F. = 7$ . Soluble in  $\text{H}_2\text{SO}_4$ . Uniaxial negative with  $N_O = 1.612\text{--}1.618$ ,  $N_E = 1.607\text{--}1.611$ ,  $N_O - N_E = 0.004\text{--}0.007$ . Color yellow to red; wax yellow in powder. Found in pegmatite in Colorado and Sweden.

**Chloraluminite**  $(\text{AlCl}_3 \cdot 6\text{H}_2\text{O})$  is rhombohedral with  $c/a = 0.534$ . Space group  $R\bar{3}c$ . Deliquescent in air. Very soluble in water. Uniaxial negative with  $N_O = 1.6+$ ,  $N_O - N_E = 0.053$ . Colorless or yellowish. Found about volcanoes.

**Fluellite**  $[\text{Al}(\text{F}, \text{OH})_3 \cdot \text{H}_2\text{O}]$  is orthorhombic dipyramidal with  $a:b:c = 0.770:1:1.878$ . Crystals pyramidal with indistinct pyramidal cleavage.  $H. = 3$ .  $G. = 2.17$ .  $F. = 7$ . Insoluble. The optic plane is 100;  $Z = c$ .  $(+)2V = 85^\circ$ ,  $r < v$  distinct.  $N_X = 1.473$ ,  $N_Y = 1.490$ ,  $N_Z = 1.511$ ,  $N_Z - N_X = 0.038$ . Again:<sup>28</sup>  $N_X = 1.490$ ,  $N_Y = 1.496$ ,  $N_Z = 1.509$ ,  $N_Z - N_X = 0.019$ . Colorless. Found in Cornwall on quartz.

### 4. Simple oxyhalides

**Eglestonite**<sup>29</sup>  $(\text{Hg}_3\text{OCl}_4)$  is isometric;  $a$  9.21 Å; U.C. 4; crystals dodecahedral with no cleavage.  $H. = 2.5$ .  $G. = 8.33$ . Volatile before the blowpipe. Decomposed by  $\text{HCl}$ . Isotropic with  $N = 2.49$  Li. Also weakly birefringent (due to strain?). Color yellow; darkens on exposure to light. Found at Terlingua, Texas.

**Bismoclite**  $(\text{BiOCl})$  is ditetragonal dipyramidal with  $c/a = 1.895$ . Space group<sup>30</sup>  $P4/nmm$ ;  $a$  3.89,  $c$  7.37 Å; U.C. 2. Crystals thin plates with basal cleavage.  $H. = 2.5$ .  $G. = 7.7$ . Uniaxial negative with  $N_O = 2.15$ ,  $N_E = ?$ .  $N_O - N_E = \text{strong}$ . Pale gray in color. Found at Goldfield, Nevada.

<sup>26</sup> C. Palache: *Mineral. Mag.*, XXIII, 573 (1934).

<sup>27</sup> P. Geijer: *Geol. För. Förh. Stockholm*, XLIII, 19 (1921).

<sup>28</sup> A. Scholz and H. Strunz: *Cent. Min. Geol.*, 1940 A, 133.

<sup>29</sup> L. S. Gawrych: *Min. Abst.*, VII, 389 (1939). Formula formerly written  $\text{Hg}_4\text{OCl}_2$ .

<sup>30</sup> W. T. Schaller: *Am. Mineral.*, XXVI, 651 (1941); E. D. Mountain: *Mineral. Mag.*, XXIV, 59 (1935).

**Daubréite**  $^{31}$   $\text{BiO}(\text{OH}, \text{Cl})$  is closely related to bismoclite; it has  $a$  3.85,  $c$  7.40 Å.  $H. = 2$ .  $G. = 6.4$ . Soluble in  $\text{HCl}$ .  $N_O = 1.91$ ,  $N_O - N_E = 0.01$  ca. Color gray. Found in Bolivia.

**Schwartzembergite**  $(\text{Pb}_{10}\text{O}_{12}\text{Cl}_6\text{I}_2)$  is pseudotetragonal with  $c/a = 0.43$ . Crystals very low pyramids with distinct 001 cleavage.  $H. = 2-2.5$ .  $G. = 7.39$ .  $F. = 1$ . Soluble in dilute  $\text{HNO}_3$ . Basal sections divide into biaxial sectors,  $2E$  varying from  $16^\circ$  to  $84^\circ$ .  $(- )2V =$  small with slight dispersion.  $N_X = 2.25$ ,  $N_Y = 2.35$ ,  $N_Z = 2.36$  Li;  $^{11} N_Z - N_X = 0.11$ . Color yellow to brown or red. Found on galena in the desert of Atacama.

**Lorettoite**  $(\text{Pb}_7\text{O}_6\text{Cl}_2)$  is probably tetragonal; massive with perfect basal cleavage.  $H. = 3$ .  $G. = 7.5$ .  $F. = 1$ . Soluble in  $\text{HNO}_3$ . Uniaxial negative with  $N_O = 2.35 - 2.40$ ,  $N_E = 2.33 - 2.37$ ,  $N_O - N_E = 0.02-0.03$ . Color orange-yellow. Found at Loretto, Tennessee.

**Kleinite**  $(\text{Hg}_2\text{OCl}_2)$  is hexagonal (above  $130^\circ \text{C.}$ ) with  $c/a = 1.664$ , in short prisms, with good basal cleavage.  $H. = 3.5$ .  $G. = 7.98$ . Sublimes at  $260^\circ \text{C.}$  Soluble in  $\text{HCl}$ . Uniaxial positive (above  $130^\circ \text{C.}$ ) with  $N_O = 2.19$ ,  $N_E = 2.21$ ,  $N_E - N_O = 0.02$ . This form is metastable at ordinary temperature. Color yellow or orange. It may invert at  $130^\circ \text{C.}$  on cooling to a biaxial negative, probably triclinic, phase with  $N_X = 2.16$ ,  $N_Y = 2.18$ ,  $N_Z = 2.18$ ,  $N_Z - N_X = 0.02$ ,  $(- )2V =$  small to medium,  $r < v$  very strong. Found at Terlingua, Texas.

**Mendipite**  $(\text{Pb}_3\text{O}_2\text{Cl}_2)$  is orthorhombic with  $^{32} a:b:c = 0.80:1:0.495$ .  $a$  9.50,  $b$  11.87,  $c$  5.87 Å. Fibrous parallel to  $c$ ; very perfect 110 and distinct 100 and 010 cleavages.  $H. = 2.5 - 2$ .  $G. = 7.0 - 7.1$ .  $F. = 1$ . Soluble in  $\text{HNO}_3$ .  $Z = c$ ;  $X = a$ .  $(+ )2V =$  nearly  $90^\circ$ ,  $r < v$  very strong;  $N_X = 2.24$ ,  $N_Y = 2.27$ ,  $N_Z = 2.31$ ,  $N_Z - N_X = 0.07$ . Colorless between parallel nicols at  $0^\circ$  and  $90^\circ$ , but gray at  $45^\circ$ . Mass color white, yellowish, bluish. Found with galena and pyrolusite in the Mendip Hills, England.

**Kempite**  $(\text{Mn}_4\text{O}_6\text{Cl}_2 \cdot 3\text{H}_2\text{O})$  is orthorhombic dipyramidal with  $a:b:c = 0.677:1:0.747$ . Crystals prismatic.  $H. = 3.5$ .  $G. = 2.94$ . Soluble in  $\text{HCl}$ . The optic plane is 010;  $X = c$ .  $(- )2V =$  moderate.  $N_X = 1.684$ ,  $N_Y = 1.695$ ,  $N_Z = 1.698$ ,  $N_Z - N_X = 0.014$ . Color emerald green. Found with pyrochroite, hausmannite, etc., in California.

**Terlinguaite**  $(\text{Hg}_2\text{OCl})$  is monoclinic with  $a:b:c = 1.605:1:2.024$ ,  $\beta = 105^\circ 37'$ . Crystals elongated along  $b$ , with perfect  $\bar{1}01$  cleavage.  $H. = 2.5$ .  $G. = 8.7$ . Volatile. The optic plane is normal to 010 and nearly normal to 100;  $Y \wedge c = +7^\circ$ . In 010, extinction is at  $39^\circ$  to the  $\bar{1}01$  cleavage.  $(- )2V = 20^\circ \pm 2^\circ$ ,  $r < v$  extreme.  $N_X = 2.35$  Li,  $N_Y = 2.64$ ,  $N_Z = 2.66$ ,  $N_Z - N_X = 0.31$ . Color sulfur yellow, greenish, brown, in a single crystal. Found at Terlingua, Texas, with eglestonite, etc.

**Cadwaladerite**  $(\text{AlOCl} \cdot 5\text{H}_2\text{O})$  is isotropic  $^{33}$  and apparently amorphous with  $G. = 1.66$  and  $N = 1.513$ . Color lemon yellow. Luster vitreous. Found on a mine dump at Cerro Pintados, Chile.

$^{31}$  F. A. Bannister: *Mineral. Mag.*, XXIV, 49 (1935).

$^{32}$  F. A. Bannister: *Mineral. Mag.*, XXIII, 587 (1934). Reports  $Bx_a \perp 100$ .

$^{33}$  S. G. Gordon: *Not. Nat. Acad. Nat. Sci. Phila.*, 80, 1941.

# B. MULTIPLE HALIDES

## 1. Multiple halides with type formula $A_mB_nX_p$ and $(m + n):p > 1:2$

**Cryolithionite** ( $\text{Li}_3\text{Na}_3\text{Al}_2\text{F}_{12}$ ) is isometric hexoctahedral. Space group <sup>34</sup>  $Ia3d$ .  $a$  12.097 Å. U.C. 3. Crystals octahedral with perfect 110 cleavage.  $H. = 3.5-4$ .  $G. = 2.78$ .  $F. = 1.5$ . Isotropic with  $N = 1.3382$  Li, 1.3395 Na, 1.3408 Tl. Colorless. Found with cryolite in Greenland.

**Mitscherlichite** ( $\text{K}_2\text{CuCl}_4 \cdot 2\text{H}_2\text{O}$ ) is tetragonal <sup>35</sup> with  $c/a = 0.7525$ . Crystals prismatic or pyramidal.  $G. = 2.42$ . Uniaxial negative with  $N_O = 1.6311$  B, 1.635 D, 1.6549 F,  $N_E = 1.6070$  B, 1.6148 D, 1.6287 F,  $N_E - N_O = 0.0217$  D (artificial crystals). Color greenish blue; pleochroic with  $O = \text{sky blue}$ ,  $E = \text{grass green}$ , and  $O > E$ . Found at Vesuvius with sylvite, metavoltite, and gypsum. A second phase is biaxial and probably orthorhombic.

**Chiolite** ( $\text{Na}_5\text{Al}_3\text{F}_{14}$ ) is ditetragonal dipyramidal <sup>35</sup> with  $c/a = 1.484$ ; space group <sup>35</sup>  $P4/mnc$ ;  $a$  7.00,  $c$  10.39 Å; U.C. 2. Crystals pyramidal with perfect 001 and distinct 111 cleavages.  $H. = 3.5-4$ .  $G. = 3$ .  $F. = 1.5$ . Uniaxial negative with  $N_O = 1.3486$ ,  $N_E = 1.3424$ ,  $N_O - N_E = 0.0062$ . Color white. Found in pegmatite in Greenland and in the Ilmen Mountains.

**Douglasite** ( $\text{K}_2\text{FeCl}_4 \cdot 2\text{H}_2\text{O}$ ) forms small crystals which are very unstable in air. Uniaxial positive with  $N_O = 1.488$ ,  $N_E = 1.500$ ,  $N_E - N_O = 0.012$ . In powder tends to lie on a face normal to an optic axis. Color green. Artificial crystals are monoclinic with  $a:b:c = 0.737:1:0.504$ ,  $\beta = 104^\circ 50'$ . Crystals prismatic or domatic (101) with poor  $\bar{2}01$  cleavage and  $G. = 2.16$ . Found in salt deposits at Stassfurt, Germany, with carnallite, etc.

**Chlormanganokalite** <sup>36</sup> ( $\text{K}_4\text{MnCl}_6$ ) is trigonal with  $c/a = 0.58$ . No cleavage.  $H. = 2.5$ .  $G. = 2.31$ .  $F. = \text{easy}$ . Deliquescent. Soluble in water. Uniaxial positive with  $N = 1.59$ ,  $N_E - N_O$  very weak. Yellow. Found at Vesuvius.

**RINNEITE**      HEXAGONAL SCALENOHEDRAL       $c/a = 0.571$        $\text{K}_3\text{NaFeCl}_6$

STRUC. Space group <sup>37</sup>  $R\bar{3}c$ ;  $a$  8.40 Å,  $\alpha$   $92^\circ 25'$ , U.C. 2.

PHYS. CHAR. Crystals rhombohedral; granular; fair prismatic cleavage.  $H. = 3$ .  $G. = 2.55$ .  $F. = \text{easy}$ . Soluble in water. Not stable in air.

OPT. PROP. Uniaxial positive with abnormal interference colors on account of strong dispersion of birefringence. The birefringence increases with rise of temperature.

$N_E =$	1.5842 Li	1.5894 Na	1.5939 Tl
$N_O =$	1.5836 Li	1.5886 Na	1.5930 Tl
$N_E - N_O =$	0.0006 Li	0.0008 Na	0.0009 Tl

Colorless or stained yellow, pink, violet, brown.

OCCUR. Found in salt deposits, as at Hildesheim, Germany.

<sup>34</sup> G. Menzer: *Zeit. Krist.*, LXXV, 265 (1930).

<sup>35</sup> F. Zambonini and G. Carobbi: *Min. Abst.*, IV, 14 (1929).

<sup>36</sup> Why not shorten this unwieldy name to the equally significant form *chlorman-kalite*?

<sup>37</sup> C. W. Cheng: *Strukturber.*, II, 494 (1937).

**Erythrosiderite** ( $K_2FeCl_5 \cdot H_2O$ ) is orthorhombic with  $a:b:c = 0.691:1:0.718$ . Crystals (100) tablets; also in crusts.  $G. = 2.32$ . Very deliquescent. The optic plane is 001;  $X = a$ .  $(- )2E = 130^\circ$  with very strong dispersion,  $r < v$ . Index estimated at 1.68, birefringence very strong. Color red; yellow in thin sections; not pleochroic, or weakly so, with  $Y =$  reddish yellow and  $X = Z =$  brownish yellow tinged with green. Found at Vesuvius, etc.

**Pseudocotunnite** ( $K_2PbCl_4$ ) is orthorhombic (?); crystals acicular.  $F. =$  easy. Soluble in warm water. Index estimated at  $N = 2$ ,  $N_Z - N_X =$  strong.  $Z$  parallel to elongation. Yellow. Found at Vesuvius.

**Weberite** ( $Na_2MgAlF_7$ ) is orthorhombic with  $a:b:c = 0.967:1:1.368$ . Space group <sup>38,39,40</sup> *Imam* or *Ima2*;  $a$  7.05,  $b$  7.29,  $c$  9.97 Å; U.C. 4.

$H. = 3.5$ .  $G. = 2.96$ . It has 101 cleavages at an angle of  $72^\circ$ .  $X = b$ ,  $Y = a$ .  $(+ )2V = 83^\circ$ ,  $N_X = 1.346$ ,  $N_Y = 1.348$ ,  $N_Z = 1.350$ ,  $N_Z - N_X = 0.004$ . Nearly colorless. Found in cryolite in Greenland.

## CARNALLITE

ORTHORHOMBIC DIPYRAMIDAL

$KMgCl_3 \cdot 6H_2O$

$a:b:c = 0.593:1:1.384$

STRUC. Space group <sup>41</sup> *Pban*;  $a$  9.54,  $b$  16.02,  $c$  22.52 Å. U.C. 12.

PHYS. CHAR. Crystals resemble hexagonal pyramids; commonly massive. No distinct cleavage.  $H. = 2.5$ .  $G. = 1.60$ .  $F. =$  easy. Deliquescent.

OPT. PROP. The optic plane is 010;  $Z = a$ .  $(+ )2V = 69^\circ 48'$ .  $r < v$  weak.  $N_X = 1.4665$ ,  $N_Y = 1.4753$ ,  $N_Z = 1.4937$ ,  $N_Z - N_X = 0.0272$ . Again:  $N_X = 1.467$ ,  $N_Y = 1.472$ ,  $N_Z = 1.497$ ,  $N_Z - N_X = 0.030$ .<sup>42</sup> Color white; reddish from hematite stain; colorless in section.

OCCUR. Found in salt deposits, as at Stassfurt, Germany, and used as a source of potash.

**Nadorite** ( $PbSbO_2Cl$ ) is orthorhombic dipyramidal with  $a:b:c = 0.458:1:0.445$ . Space group <sup>43</sup> *Cmcm*;  $a$  5.59,  $b$  12.21,  $c$  5.43 Å. U.C. 4. Crystals {100} tablets elongated along  $b$  with perfect 100 cleavage. Twinning on 011 at  $91^\circ 45'$ .  $H. = 4$ .  $G. = 7$ .  $F. = 1.5$ . Soluble in HCl.  $X = a$ ;  $Y = c$ .  $(+ )2V =$  very large,  $r > v$  strong.  $N_X = 2.30$  Li,  $N_Y = 2.35$ ,  $N_Z = 2.40$ ,  $N_Z - N_X = 0.10$ . Color smoky brown to brownish yellow. Found in zinc-ore deposits in Algeria.

**Baeumlerite** <sup>44</sup> ( $KCaCl_3$ ) is pseudocubic (orthorhombic?) with pseudocubic cleavage. Crystals prismatic or tabular; lamellar twinning.  $H. = 2.5-3$ . Strongly hygroscopic. Biaxial negative with the optic plane parallel to a pseudocubic face.  $N_Y = 1.52 \pm$ ,  $N_Z - N_X =$  weak.

<sup>38</sup> C. Brosset: *Min. Abst.*, X, 16 (1947).

<sup>39</sup> A. Byström: *Min. Abst.*, IX, 226 (1946). Described as monoclinic by R. Bøgvad: *Med. Grönland*, CXIX, No. 7 (1938).

<sup>40</sup> R. B. Ferguson: *Am. Mineral.*, XXXIV, 383 (1949). To make  $b > a$ ,  $abc$  have been changed to  $bac$ .

<sup>41</sup> K. R. Andress and O. Saffe: *Zeit. Krist.*, CI, 451 (1939).

<sup>42</sup> W. T. Schaller: *U. S. Geol. Surv. Bull.* 833, 21 (1932).

<sup>43</sup> L. G. Sillén and L. Melander: *Min. Abst.*, VIII, 365 (1943). Axes  $b$  and  $c$  interchanged to make  $b > a > c$ .

<sup>44</sup> J. Paclt: *Min. Abst.*, IX, 212 (1946).

CRYOLITE

MONOCLINIC PRISMATIC

$\text{Na}_3\text{AlF}_6$

$$a:b:c = 0.966:1:1.388 \quad \beta = 90^\circ 11'$$

STRUC. Space group  $^{45}P2_1/n$ ;  $a$  5.46,  $b$  5.61,  $c$  7.80 Å.  $\beta = 90^\circ 11'$ . U.C. 2.

PHYS. CHAR. Crystals cubic in aspect by development of {001} and {110}. Also massive, cleavable. Twinning on 110, either contact or lamellar; similarly on  $11\bar{2}$  and 100. Pseudocubic cleavage with 001 perfect and 110 good;  $10\bar{1}$  also good.  $H. = 2.5$ .  $G. = 2.95-3.0$ . Fusible at  $920^\circ\text{C}$ . Soluble in  $\text{H}_2\text{SO}_4$  with evolution of HF. Soluble in 2,720 parts of water.

OPT. PROP. The optic plane and  $X$  are normal to 010;  $Z \wedge c = +44^\circ$ . See Fig. 26. The refringence is low, giving marked relief. Strictly isotropic above  $570^\circ\text{C}$ .  $(+ )2V = 43^\circ$ ,  $r < v$ , with horizontal dispersion.  $N_x = 1.3385$ ,  $N_y = 1.3389$ ,  $N_z = 1.3396$ ,  $N_z - N_x = 0.0011$  Na. Colorless to snow white; also stained reddish, brown, black.

INVER. Reversible inversion to an isometric form at about  $560^\circ\text{C}$ .

ALTER. Several hydrous fluorides form by alteration; these include *pachnolite*, *thomsenolite*, *prosopite*, and *gearsulite*.

OCCUR. Cryolite is obtained from a pegmatite in gneiss in west Greenland, where it is associated with quartz, fluorite, siderite, cassiterite, galena, molybdenite, etc. Also known in pegmatite with quartz, microcline, and zircon near Pikes Peak, Colorado, and in a topaz mine in the Ilmen Mountains.

Elpasolite  $^{46}(\text{K}_2\text{NaAlF}_6)$  is isometric with  $a = 8.093$ , U.C. 4. Crystals equant.  $H. = 2.5$ .  $G. = 3.0$ . No cleavage. Isotropic with  $N = 1.376$ . An alteration product of cryolite in El Paso County, Colorado.

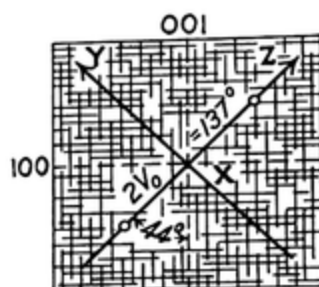


FIG. 26. The optic orientation of cryolite.

## 2. Multiple halides with type formula $A_mB_nX_p$ and $(m+n):p = 1:2$

**Hieratite** ( $\text{K}_2\text{SiF}_6$ ) is isometric hexoctahedral with perfect 111 cleavage. Space group  $Fm\bar{3}m$ ;  $a$  8.17 Å; U.C. 4.  $G. = 2.75$ . Soluble in hot water. Isotropic with  $N = 1.40$ , as measured on crystals from Vesuvius.  $N = 1.34$  as measured on artificial crystals which serve as a microchemical test for potassium. Found about volcanoes, as at Hieria on the Lipari Islands.

**Cryptohalite**  $[(\text{NH}_4)_2\text{SiF}_6]$  is isometric hexoctahedral with perfect 111 cleavage. Space group  $Fm\bar{3}m$ ;  $a$  8.34 Å. U.C. 4.  $G. = 2.00$ . Soluble in hot water. Isotropic with  $N = 1.369$  Na. Also hexagonal with  $c/a = 1.083$ . Crystals basal tablets with perfect basal cleavage.  $G. = 2.15$ . Uniaxial negative with  $N_O = 1.406$ ,  $N_E = 1.391$ ,  $N_O - N_E = 0.015$ . Colorless. Found at Vesuvius.

**Diaboléite**  $[\text{Pb}_2\text{Cu}(\text{OH})_4\text{Cl}_2]$  is ditetragonal pyramidal  $^{47}$  with  $c/a = 0.936$ ; space group  $P4mm$ ;  $a$  5.83,  $c$  5.46 Å; crystals pyramidal with perfect basal cleavage.  $H. = 2.5$ .  $G. = 5.42$ .  $F. = \text{easy}$ . Soluble in  $\text{HNO}_3$ . Uniaxial negative with

$^{45}$  I. Náray-Szabó and K. Sasvári: *Zeit. Krist.*, XCIX, 27 (1938).

$^{46}$  C. Frondel: *Am. Mineral.*, XXXIII, 84 (1948).

$^{47}$  C. Palache: *Am. Mineral.*, XXVI, 605 (1941).



$N_O = 1.98$ ,  $N_E = 1.85$ ,  $N_O - N_E = 0.13$ . Color sky blue with  $X =$  pale blue to colorless,  $Z =$  deep blue. Found in ore deposits, as in Pinal County, Arizona.

**Tachyhydrite** ( $Mg_2CaCl_6 \cdot 12H_2O$ ) is trigonal with  $c/a = 1.90$ ; distinct rhombohedral cleavage. Soft.  $G. = 1.67(?)$ .  $F. = 1$ . Very deliquescent. Uniaxial negative with  $N_O = 1.522$ ,  $N_E = 1.513$ ,  $N_O - N_E = 0.009$ . Color wax to honey yellow. Found in salt deposits with carnallite, anhydrite, etc., as at Stassfurt, Germany.

**Malladrite** <sup>47a</sup> ( $Na_2SiF_6$ ) is pseudo-hexagonal (orthorhombic) with  $c/a = 0.564$ . Crystals prismatic with pseudo-hexagonal twinning.  $G. = 2.75$ . Nearly uniaxial, and negative.  $N_O = 1.312$ ,  $N_E = 1.309$ ,  $N_O - N_E = 0.003$ . Colorless. Found at Vesuvius. Crystals serve as a microchemical test for sodium.

**Avogadrite** <sup>48</sup> ( $KBF_4$  with about 10% of  $CsBF_4$ ) is orthorhombic with  $a:b:c = 0.790:1:1.283$ . Space group  $Pnm$ . Crystals {001} tablets elongated parallel to  $b$  (or  $a$ ).  $G. = 2.62$ . The optic plane is 010;  $X = c$ .  $(- )2V =$  very large.  $N_X = 1.3239$  Na,  $N_Y = 1.3245$  Na, 1.3253 (677),  $N_Z = 1.3247$  Na, 1.3326 (677),  $N_Z - N_X = 0.0008$  Na. Colorless. Found at Vesuvius.

**Ferruccite** ( $NaBF_4$ ) is orthorhombic dipyramidal <sup>49</sup> with  $a:b:c = 0.917:1:0.993$ . Space group  $Ccmm$ ;  $a$  6.25,  $b$  6.82,  $c$  6.77 Å. U.C. 4. Crystals {010} and {001} tablets.  $G. = 2.50$ . Soluble in water. The optic plane is 010;  $X = c$ .  $(+)2V = 11^\circ 25'$ .  $N_X = 1.301$ ,  $N_Y = 1.3012$ ,  $N_Z = 1.3068$ ,  $N_Z - N_X = 0.0058$ . A fumarolic product at Vesuvius.

**Pachnolite** ( $NaCaAlF_6 \cdot H_2O$ ) is monoclinic with  $a:b:c = 1.163:1:1.532$ ,  $\beta = 90^\circ 20'$ . Space group <sup>50</sup>  $C2/c$  or  $Cc$ .  $a$  12.12,  $b$  10.39,  $c$  15.68 kX. U.C. 16. Crystals prismatic with poor basal cleavage. Twinning on 100.  $H. = 3$ .  $G. = 2.98$ .  $F. = 1.5$ . Soluble in  $H_2SO_4$ . The optic plane and  $X$  are normal to 010;  $Z \wedge c = +68^\circ$ .  $(+)2V = 76^\circ$ ,  $r < v$  weak; strong horizontal dispersion;  $N_X = 1.407$ ,  $N_Z = 1.418$ ,  $N_Z - N_X = 0.011$ , <sup>51</sup>  $\therefore N_Y = 1.411$  (calc.). Colorless. An alteration product of cryolite in Greenland, etc.

**Thomsenolite** ( $NaCaAlF_6 \cdot H_2O$ ) is monoclinic prismatic with  $a:b:c = 1.013:1:2.927$ ,  $\beta = 96^\circ 27'$ . Space group <sup>50</sup>  $P2_1/c$ .  $a$  5.57,  $b$  5.50,  $c$  16.10 Å. U.C. 4. Perfect basal and poor prismatic cleavages.  $H. = 2$ .  $G. = 2.98$ .  $F. = 1.5$ . Decomposed by  $H_2SO_4$ . The optic plane and  $Z$  are normal to 010;  $X \wedge c = +52^\circ$ .  $(-)2V = 50^\circ$ ,  $r < v$  weak.  $N_X = 1.407$ ,  $N_Y = 1.4136$ ,  $N_Z = 1.415$ ,  $N_Z - N_X = 0.008$ . Colorless. Alteration product of cryolite.

### 3. Multiple halides with type formula $A_mB_nX_p$ and $(m + n):p < 1:2$

**Ralstonite** [ $Na_3Mg_3Al_{13}(F,OH)_{48} \cdot 7H_2O?$ ] is isometric hexoctahedral. Space group <sup>52</sup> probably  $Fd3m$ ;  $a$  9.87 Å; U.C. 1. Crystals octahedral with no cleavage.  $H. = 4.5$ .  $G. = 2.61$  (varies).  $F. = 7$ . Decomposed by  $H_2SO_4$ . Isotropic with  $N = 1.43$ , <sup>52</sup> 1.399. <sup>53</sup> Also weakly birefringent in octahedral segments which have

<sup>47a</sup> F. Zambonini and G. Carobbi: *Atti R. Acad. Lincei Roma*, (6) IV, 171 (1926).

<sup>48</sup> F. Zambonini: *Atti R. Accad. Lincei Roma*, (6) III, 644 (1926).

<sup>49</sup> G. Carobbi: *Per. Min. Roma*, IV, 410; *Min. Abst.*, V, 390 (1933).

<sup>50</sup> R. B. Ferguson: *Trans. Roy. Soc. Can.*, XL, Sect. IV, 11 (1946).

<sup>51</sup> K. K. Landes: *Am. Mineral.*, XX, 319 (1935).

<sup>52</sup> A. Pabst: *Am. Mineral.*, XXIV, 566 (1939).

<sup>53</sup> S. G. Gordon: *Not. Nat. Acad. Sci. Phila.*, 11, 1939.

a very large optic angle. Colorless to yellow. At  $445^{\circ}$  loses its water and becomes strictly isotropic with  $G. = 2.3$  and  $N = 1.39$ . Found with cryolite in Greenland.

**Yttrocalsite** ( $\text{Ca}_5\text{Y}_2\text{F}_{16}$ ) is hexagonal with  $c/a = 0.711$ . Crystals prismatic with distinct prismatic cleavage.  $H. = 4-6$ .  $G. = 3.19$ .  $F. = 7$ . Soluble in acid. Uniaxial negative with index estimated at 1.45 and very weak birefringence. White to greenish. Found in Norway.

**Jarlite** ( $\text{NaSr}_3\text{Al}_3\text{F}_{16}$ ?) is monoclinic<sup>54</sup> with  $a:b:c = 1.46:1:2.58$ ,  $\beta = 110^{\circ} 40'$ . In a different orientation Ferguson found  $a:b:c = 1.478:1:0.669$ ,  $\beta = 101^{\circ} 49'$ , with  $a$  15.99,  $b$  10.82 and  $c$  7.24. Crystal {100} tablets, elongated along  $b$ .  $H. = 3-4$ .  $G. = 3.93$ . Soluble in  $\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$ . The optic plane is 010;  $Z \wedge c = 74^{\circ}$ ;  $^{54} Z \wedge c = 84^{\circ}$ .<sup>55</sup>  $(- )2V = 78^{\circ}$  to  $90^{\circ}$  and  $(+)2V = 90^{\circ}$  to  $82^{\circ}$ .  $N_X = 1.427$ ,<sup>54</sup>  $N_Y = 1.432-3$ ,  $N_Z = 1.435$ ,  $N_Z - N_X = 0.008$ . Again<sup>55</sup>  $N_X = 1.430$ ,  $N_Y = 1.435$ ,  $N_Z = 1.437$ ,  $N_Z - N_X = 0.007$ . Colorless or brownish. Found only at Ivigtut, Greenland.

**Gearksutite** [ $\text{CaAl}(\text{F},\text{OH})_5 \cdot \text{H}_2\text{O}$ ] is monoclinic, acicular, or powdery.  $H. = 2$ .  $G. = 2.72-2.77$ .  $F. = 1.5-2$ . Soluble in acid.  $X$  is normal to 010;  $Z \wedge c = \text{small}$ .  $(- )2V = \text{medium}$ .  $N_X = 1.448$ ,  $N_Y = 1.454$ ,  $N_Z = 1.456$ ,  $N_Z - N_X = 0.008$ . White, chalky. Alteration product of cryolite.

**Prosopite** [ $\text{CaAl}_2(\text{F},\text{OH})_8 \cdot \text{H}_2\text{O}$ ] is monoclinic prismatic with  $a:b:c = 1.319:1:0.595$ ,  $\beta = 94^{\circ} 20'$ . Space group  $C2c$ ;  $a$  6.67,  $b$  11.17,  $c$  7.37. Tabular parallel to 010, with distinct 211 cleavage.  $H. = 4.5$ .  $G. = 2.88$ .  $F. = 7$ . Decomposed by  $\text{H}_2\text{SO}_4$ . The optic plane is 010;  $Z \wedge c = +50^{\circ}$ ,  $Z$  nearly parallel to the edge made by the cleavages 211 and  $2\bar{1}1$ .  $(+)2V = 63^{\circ}$ ,  $r > v$  marked.  $N_X = 1.501$ ,  $N_Y = 1.503$ ,  $N_Z = 1.519$ ,  $N_Z - N_X = 0.009$ . Colorless. An alteration product of cryolite.

#### 4. Multiple oxyhalides

**Percylite** ( $\text{PbCuOCl}_2 \cdot \text{H}_2\text{O}$ ) is isometric. Crystals cubic with cubic cleavage.  $H. = 2$ .  $G. = 2.25$ .  $F. = 1$ . Soluble in  $\text{HNO}_3$ . Isotropic with  $N = 2.05$ ; partly altered to boléite,  $N = 2.06$ ,  $N_Z - N_X = 0.02$ . Blue; sky blue in section. Found with lead ores in the oxide zone, as at Sonora, Mexico.

**BOLÉITE** TETRAGONAL  $c/a = 3.996$   $\text{Pb}_9\text{Cu}_3\text{Ag}_3\text{O}_8\text{Cl}_{21} \cdot 9\text{H}_2\text{O}$

STRUC.<sup>56</sup>  $a$  15.4,  $c$  62. Å; U.C. 12.

PHYS. CHAR. Crystals pseudocubic with perfect 001 and 101 cleavages.  $H. = 2.5$ .  $G. = 4.8 - 5.1$ .  $F. = 1$ . Soluble in  $\text{HNO}_3$ .

OPT. PROP. Uniaxial negative with  $N_O = 2.04 - 2.09$ ,  $N_E = 2.03$  ca.  $N_O - N_E = 0.02$  ca. Color indigo blue. In section greenish blue, not pleochroic. Crystals have an isotropic center supposed to be due to mingling of three twinned parts which form the borders, each part forming two opposite faces of the pseudocube.

OCCUR. Found at Boléo, southern California, etc.

**Cumengéite** ( $\text{Pb}_4\text{Cu}_4\text{O}_4\text{Cl}_8 \cdot 5\text{H}_2\text{O}$ ) is ditetragonal dipyramidal with  $c/a = 1.625$ ; space group<sup>57</sup>  $I4/mmm$ ;  $a$  14.9,  $c$  24.15 Å; U.C. 10. Distinct 101 and poor 110

<sup>54</sup> R. Bøggvad: *Med. Grönland*, XCII, No. 8 (1933).

<sup>55</sup> R. B. Ferguson: *Bull. Geol. Soc. Am.*, LVIII, 1179 (1947); *Am. Mineral.*, XXXIV, 383 (1949).

<sup>56</sup> R. Hocart: *Bull. Soc. Fr. Min.*, LVII, 5 (1934).

<sup>57</sup> R. Hocart: *Zeit. Krist.*, LXXIV, 20 (1930); B. Gossner and M. Arm: *Zeit. Krist.*, LXXII, 202 (1929).

cleavages.  $H. = 2.5$ .  $G. = 4.7-4.8$ .  $F. = 1$ . Soluble in  $HNO_3$ . Uniaxial negative with  $N_O = 2.041$  (510),  $N_E = 1.926$ ,  $N_O - N_E = 0.115$ . Color indigo blue; purer blue in section than boléite or pseudoboléite, with which it is intergrown; differs from them also in lack of pearly luster on cleavage faces. Pleochroic with  $E =$  clear blue,  $O =$  slightly darker and greenish blue. The physical characters show distinct variations, probably due to variations in composition. Found with boléite in southern California.

**Pseudoboléite** ( $Pb_5Cu_4O_4Cl_{10} \cdot 6H_2O$ ) is tetragonal with  $c/a = 2.023$ ;  $a$  <sup>58</sup> 15.41,  $c$  31.2 Å. U.C. 12. Perfect 001 and 101 cleavages.  $H. = 2.5$ .  $G. = 4.85$ .  $F. = 1$ . Soluble in  $HNO_3$ . Uniaxial negative with  $N_O = 2.03$ ,  $N_E = 2.00$ ,  $N_O - N_E = 0.032-0.038$ . Color indigo blue. Not pleochroic. Found only in parallel intergrowth with boléite.

**Nocerite** ( $Ca_3Mg_3O_2F_8$ ) is hexagonal with  $c/a = 0.355$ ; space group <sup>59</sup>  $C6$  or  $C6/m$ .  $a$  8.84,  $c$  3.12 Å. U.C. 3. Crystals acicular.  $G. = 2.96$ . Uniaxial negative with  $N_O = 1.5073$  (633), 1.5084 Na, 1.5131 (475),  $N_E = 1.486$ ,  $N_O - N_E = 0.023$ ; <sup>60</sup>  $N_O = 1.512$ ,  $N_E = 1.487$ ,  $N_O - N_E = 0.025$ .<sup>11</sup> White. Found in volcanic bombs (with fluorite) at Nocera, Italy.

**Koenenite** ( $Mg_5Al_2O_6Cl_4 \cdot 6H_2O$ ) is trigonal with perfect basal cleavage. Very soft.  $G. = 1.98$ . Uniaxial positive with strong birefringence; refringence unknown. Color red (due to enclosed hematite) to pale yellow. Decomposed by water without change of shape, the residue ( $Al_2O_3$ ) being uniaxial negative with weak birefringence. Found in salt deposits with carnallite, as at Sarstedt, Germany.

**Chloroxiphite** <sup>61</sup> [ $Pb_3CuO_2(OH)_2Cl_2$ ] is monoclinic with  $\beta = 117^\circ 15'$ . Crystals elongated parallel to  $b$ , with perfect 001 and distinct 100 cleavages.  $H. = 2.5$ .  $G. = 6.76$ .  $F. =$  easy. Soluble in  $HNO_3$ . The optic plane and  $Z$  are normal to 010;  $X \wedge c =$  small.  $(- )2H = 80^\circ$ ,  $N =$  very high,  $N_Z - N_X =$  very strong. Color green with  $a =$  yellowish brown,  $b = Z =$  emerald green. Found in ore deposits in the Mendip Hills, England.

<sup>58</sup> G. Friedel: *Zeit. Krist.*, LXXIII, 147 (1930); R. Hocart: *Zeit. Krist.*, LXXIV, 20 (1930).

<sup>59</sup> A. Scherillo: *Per. Min. Roma*, IX, 229 (1938).

<sup>60</sup> F. Zambonini: *Zeit. Krist.*, LVI, 219 (1921).

<sup>61</sup> L. J. Spencer and E. D. Mountain: *Mineral. Mag.*, XX, 75 (1923).



### III. SULFIDES

Sulfides, selenides, tellurides, arsenides, antimonides, oxysulfides, and multiple sulfides or sulfosalts are included in this division. All transparent and translucent minerals are included if their optic properties are known, but only a few of the more important opaque minerals are described. The arrangement is according to the decreasing A to X ratio in sulfides and the (A + B) to X ratio in the multiple sulfides, A representing the metallic elements, B the semimetal elements like As in multiple sulfides, and X the nonmetallic elements, especially S. Sphalerite has homopolar bonding, but many sulfides have ionic bonding.

An outline classification of sulfides follows:

A. Simple sulfides.

1. Simple sulfides with type formula  $A_2X$ .
2. Simple sulfides with type formula  $A_3X_2$ .
3. Simple sulfides with type formula  $AX$ .
4. Simple sulfides with type formula  $A_2X_3$ .
5. Simple sulfides with type formula  $AX_2$ .

B. Multiple sulfides (or sulfosalts)

1. Multiple sulfides with type formula  $A_mB_nX_p$  and  $(m+n):p > 1:1$ .
2. Multiple sulfides with type formula  $A_mB_nX_p$  and  $(m+n):p = 1:1$ .
3. Multiple sulfides with type formula  $A_mB_nX_p$  and  $(m+n):p < 1:1$ .

#### A. SIMPLE SULFIDES

##### 1. Simple sulfides with type formula $A_2X$

**CHALCOCITE** (*Chalkosine*) ORTHORHOMBIC DIPYRAMIDAL<sup>1</sup>  
 $a:b:c = 0.437:1:0.496$

$Cu_2S$

COMP. May contain up to about 8% CuS in crystal solution.

STRUC.<sup>2</sup> Space group probably  $Cmmm$ ;  $a$  11.8,  $b$  27.2,  $c$  22.7 Å. U.C. 160. Again:<sup>1</sup>  
 $a$  11.8,  $b$  27.0,  $c$  13.4 Å. U.C. 96.

<sup>1</sup> I. Oftedal: *Norsk. Geol. Tidsk.*, XXIV, 114 (1944).

<sup>2</sup> N. Alsen: *Geol. För. Förh. Stockholm*, LIII, 111 (1931). X-ray:  $b/4:a:c/2 = 0.576:1:0.963$ . Oftedal, ref. 1, gives  $c$  13.4, U.C. 96.

**PHYS. CHAR.** Crystals may be hexagonal in aspect; poor prismatic cleavage.  $H. = 2.5-3$ .  $G. = 5.5-5.8$  (5.78 pure). Fuses at  $1130^{\circ} \text{C}$ . Soluble in  $\text{HNO}_3$ .

**OPT. PROP.** Color blackish lead gray. Opaque. In inclined reflected light has metallic luster and dark lead gray color; bluish white in vertically reflected light. In polished section weakly anisotropic.<sup>3</sup> Reflection percentages: red 15, orange 16, green 22.5. After etching, produces a noticeable rotation of the plane of polarization of reflected light.

**INVER.** Changes to a hexagonal form<sup>4</sup> with  $c = 1.717$  and  $G. = 5.65$  at  $105^{\circ} \text{C}$ .; the reverse change occurs promptly on cooling.

**ALTER.** Tarnish not uncommon; may alter to covellite or chalcopyrite or bornite.

**OCCUR.** Chiefly in veins with chalcopyrite, bornite, enargite, etc., as at Ely, Nevada; Butte, Montana; and in Chile; Peru; and Mexico. Also formed by action of hot spring water on coins.

**Acanthite** ( $\text{Ag}_2\text{S}$ ) is monoclinic prismatic<sup>5</sup> with  $a:b:c = 1.368:1:1.96$ ,  $\beta = 124^{\circ}$  and  $a$  9.47,  $b$  6.92,  $c$  8.28 Å. Space group  $B2_1/c$ . U.C. 8. Multiple twinning on 001. Crystals prismatic with no good cleavage.  $H. = 2.5$ .  $G. = 7.2-7.3$ .  $F. = 1.5$ . Soluble in  $\text{HNO}_3$ . Opaque. Luster metallic. Color and streak blackish lead gray; in vertical reflected light grayish white. Changes (reversibly) to an isometric form<sup>6</sup> (*argentite*, whose space group is  $Im\bar{3}m$ ;  $a$  4.88; U.C. 2) at about  $179^{\circ} \text{C}$ . Found chiefly in veins often associated with galena; also with copper or gold ores. Localities include Freiberg, Saxony; Georgetown, Colorado; Butte, Montana; etc.

## 2. Simple sulfides with type formula $\text{A}_3\text{X}_2$

### BORNITE

#### ISOMETRIC HEXOCTAHEDRAL



**STRUC.**<sup>7</sup> Space group  $Fd\bar{3}m$ ;  $a$  10.93 Å. U.C. 8.

**PHYS. CHAR.** Crystals cubic or modified. No cleavage.  $H. = 3$ .  $G. = (4.9-5.07)$ . Soluble in  $\text{HNO}_3$  with separation of sulfur.

**OPT. PROP.** Opaque. Color reddish brown, seen only on fresh fracture, which tarnishes quickly to red and blue. Streak pale grayish black. In vertically reflected light pinkish brown. Reflection percentages;<sup>3</sup> red 21, orange 19, green 18.5.

**OCCUR.** Chiefly in veins with chalcopyrite, chalcocite, etc.; also in pegmatites. Formed by action of hot spring water on coins; also in copper furnaces. Localities include Redruth, Cornwall; Androta, Madagascar; Butte, Montana; Bisbee, Arizona; etc.

## 3. Simple sulfides with type formula $\text{AX}$

### GALENA

#### ISOMETRIC HEXOCTAHEDRAL



**STRUC.**<sup>8</sup> Space group  $Fm\bar{3}m$ ;  $a$  5.95 Å. U.C. 4.

**PHYS. CHAR.** Crystals, cubes, octahedrons, etc., with perfect cubic

<sup>3</sup> H. Schneiderhöhn and P. Ramdohr: *Lehrb. Erzmikr.*, II (1931).

<sup>4</sup> N. W. Buerger: *Econ. Geol.*, XXXVI, 19 (1941).

<sup>5</sup> L. S. Ramsdell: *Am. Mineral.*, XXVIII, 401 (1943).

<sup>6</sup> R. C. Emmons, C. H. Stockwell, and R. H. B. Jones: *Am. Mineral.*, XI, 326 (1926).

<sup>7</sup> D. Lundquist and A. Westgren: *Ark. Kemi*, XIIB, No. 23 (1936).

<sup>8</sup> V. M. Goldschmidt: *Strukturber.*, I, 131 (1931).

cleavage.<sup>8,9</sup> H. = 2.5. G. = 7.5. F. = 2 (M.P. = 1115° C.). Decomposed by H<sub>2</sub>SO<sub>4</sub>.

OPT. PROP. Opaque. Color and streak lead gray. Luster metallic. N = 4.015 C, 3.912 D, 3.796 F. Polishes readily, giving isotropic surface; in vertically reflected light, galena white. Reflection percentages: <sup>3</sup> red 35, orange 37.5, green 33.5.

ALTER. Alters rather easily to cerussite; also to anglesite, pyromorphite, mimetite, wulfenite, linarite, minium.

OCCUR. Galena is one of the most widely distributed of the sulfides. It is found in quartz veins, in rocks of all kinds, often associated with ores of zinc, copper, or silver; it is abundant in some calcite (or dolomite) veins, and in disseminated deposits in sedimentary rocks often associated with sphalerite, pyrite, marcasite, and various carbonates. It occurs less commonly as a product of contact metamorphism; also found as a result of the action of hot springs on coins; and as a furnace product.

**Alabandite** (MnS) is also isometric hexoctahedral; space group <sup>10</sup> *Fm3m* with  $a = 5.21 \text{ \AA}$ . U.C. 4. Usually granular massive; perfect cubic cleavage. H. = 3.5–4. G. = 3.9–4.04. F. = 3. Soluble in HCl. Translucent in very thin splinters with N = 2.70 Li. Isotropic. Luster submetallic. Color iron black with brown tarnish; streak green. In vertically reflected light grayish white. Reflection percentages: <sup>3</sup> red 20, orange 21, green 24. Found chiefly in metalliferous veins, as at Kapnik, Rumania; Bisbee, Arizona; etc.; formed in steel furnaces.

**Oldhamite** (CaS) is isometric hexoctahedral; space group <sup>11</sup> *Fm3m* with  $a = 5.686 \text{ \AA}$ ; U.C. 4. Cubic cleavage. H. = 4. G. = 2.58. Infusible. Color pale chestnut brown. Isotropic with N = 2.137. Found rarely in meteorites.

## SPHALERITE (*Blende*) ISOMETRIC HEXTETRAHEDRAL (Zn,Fe)S

STRUC. Space group *F43m*;  $a = 5.40 \text{ \AA}$ ; U.C. 4.

COMP. Iron may replace up to 28% of the zinc; Mn and Cd often present in small amount.

PHYS. CHAR. Crystals tetrahedral, often complex. Twinning on 111. Perfect dodecahedral cleavage. H. = 3.5–4. G. = 3.9–4.1, decreasing with increase of iron. (See Fig. 27.) Infusible or nearly so. Sublimes in N at 1178° C. Soluble in HCl.

OPT. PROP. Isotropic; rarely anisotropic probably on account of strain, since anisotropic areas are easily produced by pressure with a pin-

<sup>9</sup> Galena containing about 1% Bi has octahedral cleavage; see I. Oftedal: *Norsk Geol. Tidssk.*, XXII, 62 (1943).

<sup>10</sup> R. W. G. Wyckoff: *Am. Jour. Sci.*, CCII, 239 (1921).

<sup>11</sup> W. P. Davey: *Phys. Rev.*, XXI, 213 (1923).

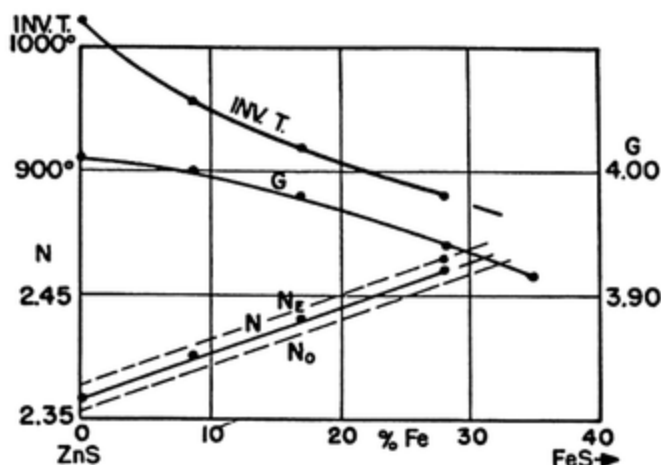


FIG. 27. Properties of sphalerite (and  $N_E$  and  $N_O$  for wurtzite).

point on a section. Refrindex extremely high and varying with tenor of iron as follows (see also Fig. 27):

Mol. % FeS	N (Li)	N (Na)	N (Tl)	$N_F - N_C$	G.	Inversion	Locality
0.2	2.340	2.369	2.399	0.091	4.09	1020°	Sonora
8.6	2.36	2.40		0.12±	4.02	955°	Spain
17.0	2.38	2.43		0.15±	3.98	919°	Australia
28.2	2.395	2.47		0.23±	3.94	880°	Saxony

Amorphous ZnS has  $N = 2.18$  to  $2.25$ .

Color brown, black, yellow; rarely green, red, colorless. Streak white to brown; in thin section may show zonal distribution of color. Resinous adamantine luster. Transparent to translucent. Rarely triboluminescent. In vertical reflected light gray. Reflection percentages: <sup>3</sup> red 18, orange 14.5, green 18.5.

INVER. Sphalerite with 0.2% FeS inverts to wurtzite at 1020° C.; 28% FeS lowers this temperature to 880° C.; CdS raises it.

OCCUR. Common in veins often associated with galena; also with chalcopyrite, tetrahedrite, calcite, siderite, quartz, fluorite, and barite. Localities include Kapnik, Rumania; Cananea, Mexico; Mineral Point, Wisconsin; Franklin, New Jersey; etc.

## CHALCOPYRITE



TETRAGONAL SCALENOHEDRAL  $c/a = 1.97$

STRUC.<sup>12</sup> Space group  $I\bar{4}2d$ ;  $a$  5.24,  $c$  10.30 Å. U.C. 4.

PHYS. CHAR. Crystals commonly tetrahedral in aspect, often striated. Twinning on 112.  $H. = 3.5-4$ .  $G. = 4.1-4.3$ .  $F. = 2$  to magnetic globule. Soluble in  $\text{HNO}_3$  with separation of S.

<sup>12</sup> L. Pauling and L. O. Brockway: *Zeit. Krist.*, LXXXII, 188 (1932).

**OPT. PROP.** Opaque. Color brass yellow, often tarnished. Luster metallic. Streak greenish black. In vertically reflected light yellow. Polished surface is weakly anisotropic purple and green and often shows lamellar twinning. Reflection percentages:<sup>3</sup> red 40, orange 40.5, green 41.5. Optically negative.<sup>13</sup>

**ALTER.** Chalcopyrite may oxidize to sulfates; other alteration products include malachite, azurite, chrysocolla, and limonite.

**OCCUR.** Chalcopyrite is the most widely disseminated ore of copper. It occurs frequently in veins with other copper minerals; it is also found disseminated in crystalline schists and gneiss, and in serpentine. Less commonly it is found in igneous rocks. It is produced by the action of hot springs upon copper coins, and is sometimes formed in metallurgical furnaces.

**WURTZITE** DIHEXAGONAL PYRAMIDAL  $c/a = 1.635$  ZnS

**STRUC.**<sup>14</sup> Space group  $C6mc$ ;  $a$  3.811,  $c$  6.234 Å; U.C. 2.

**PHYS. CHAR.** Crystals hemimorphic, short prismatic or pyramidal with easy prismatic cleavage.  $H. = 3.5-4$ .  $G. = 3.98-4.08$ . Sublimes at  $1185^{\circ}\text{C.}$ ; re-forms on cooling. Soluble in HCl.

**OPT. PROP.** Uniaxial positive with  $N_O = 2.356$  Na,  $N_E = 2.378$ ,  $N_E - N_O = 0.022$ ; also  $N_O = 2.330$  Li,  $N_E = 2.350$ . Apparently isotropic in Canada balsam, but plainly anisotropic in S-Se melts. Commonly fibrous to lamellar parallel to 0001 with negative elongation. Luster resinous. Streak brown. Color yellow to black like sphalerite; feebly pleochroic in yellow with  $X > Z$ ; in thicker plates:  $X =$  yellow,  $Z =$  brown. Gray in vertically reflected light.

**OCCUR.** In metalliferous veins; forms only from acid solutions; the stable form of ZnS above  $1020^{\circ}\text{C.}$ , but inverts very slowly at lower temperatures. Formed artificially only above  $200^{\circ}\text{C.}$  Found at Mies, Bohemia; Oruro, Bolivia; Butte, Montana; etc.

**DIAG.** Distinguishable only by optical properties from sphalerite when crystal form is lacking, but a fibrous condition is suggestive of wurtzite.

**Greenockite** (CdS) is dihexagonal pyramidal with  $c/a = 1.622$ . Space group <sup>15</sup>  $C6mc$ ;  $a$  4.142,  $c$  6.724 Å. Crystals hemimorphic, short prismatic, with distinct prismatic cleavage.  $H. = 3-3.5$ .  $G. = 4.82$ . M.P.  $780^{\circ}\text{C.}$  Soluble in HCl. Uniaxial positive for red to blue-green, negative from blue-green to blue; isotropic for  $\lambda = 523$ .  $N_O = 2.506$  Na,  $N_E = 2.529$ ,  $N_E - N_O = 0.023$ , and  $N_O = 2.431$  Li,  $N_E = 2.456$  (art. cryst.). For  $N_O$ ,  $N_F - N_C = 0.23$  ca. Natural crystals gave  $N_O = 2.582$  red,  $N_E - N_O =$  weak; sometimes distinctly biaxial. Color yellow of various shades; pleochroism weak. Found in cavities in basic igneous rocks, but more common in zinc ore deposits in small amounts, coloring smithsonite or coating sphalerite. Found at Bishopston, Scotland; Paterson, New Jersey; Topaz, California; etc.

**Voltzite** ( $\text{Zn}_5\text{OS}_4$ ) is hexagonal in lamellar or finely fibrous compact globular forms.  $H. = 4-4.5$ .  $G. = 3.7-3.8$ .  $F. = 7$ . Attacked by HCl. Uniaxial positive with  $N_O = 2.03$  ca.  $N_E - N_O =$  rather strong. Color dirty rose-red, yellow, or

<sup>13</sup> L. Capdecombe: *Bull. Soc. Fr. Min.*, LXIV, 171 (1941).

<sup>14</sup> M. L. Fuller: *Phil. Mag.*, VIII, 658 (1929).

<sup>15</sup> W. L. Bragg: *Phil. Mag.*, XXXIX, 647 (1920); *Structurber.*, I, 129 (1931).

brown. Colorless in thin section. Brown in inclined reflected light; gray in vertically reflected light. Alters in immersion liquids. Found at the Elias mine, Bohemia; Lahr, Baden; and the Rosières mine, France.

## PYRRHOTITE



DIHEXAGONAL DIPYRAMIDAL  $c/a = 3.30$

STRUC. Space group <sup>16</sup>  $C6_32(?)$ ;  $a$  6.87,  $c$  22.7 Å. U.C. 32. A monoclinic phase is also known,<sup>17</sup> with  $a$  5.94,  $b$  3.43,  $c$  5.68 Å,  $\beta = 90^\circ 30'$ ; it inverts to hexagonal at 500°.

COMP. Fe is slightly deficient (except in *troilite*),  $n$  ranging from 0 to 0.2; may contain a little Ni, Co, Mn.

PHYS. CHAR. Crystals commonly hexagonal prisms or basal plates. Twinning on  $10\bar{1}2$  rare. Basal parting.  $H. = 3.5\text{--}4.5$ .  $G. = 4.77$  (for FeS) to 4.53 (for  $\text{Fe}_{0.85}\text{S}$ ). Fuses at about 1170° C. to black magnetic mass. Soluble in HCl. Pyrrhotite is magnetic, but to a very variable degree.

OPT. PROP. Opaque. Luster metallic. Streak dark grayish black. Color between bronze yellow and copper red, darker than pyrite; subject to tarnish. Cream color in vertically reflected light. Optically positive.<sup>13</sup> Polished surface strongly anisotropic and weakly pleochroic, producing marked rotation of the plane of polarization. Reflection percentages; <sup>3</sup> red 36, orange 37, green 37.

INVER. The stable form above 130° C. is orthorhombic with  $a:b:c = 0.579:1:0.927$  (to 0.993). Inversion is not easily accomplished.

ALTER. In the presence of sulfur pyrrhotite tends to change to pyrite, especially at temperatures of 100–300° C., in air it alters easily to limonite.

OCCUR. Pyrrhotite is found in basic and especially nephelinitic igneous rocks, and, much more rarely, in acid types. It also occurs in amphibolite, in crystalline schists, and in rocks produced by contact metamorphism. The largest masses are found in metalliferous veins. Finally it occurs in meteorites—ordinary pyrrhotite in stony meteorites and *troilite* in iron meteorites. Localities include Leoben, Austria; Snarum, Norway; Ducktown, Tennessee; Kimberley, British Columbia; etc.

DIAG. Distinguished from pyrite by the color, the crystal form, the density, the magnetism, and the attack by HCl.

**Niccolite** (NiAs) is dihexagonal dipyramidal with  $c/a = 1.397$ ; space group <sup>18</sup>  $C6/mmc$ ;  $a$  3.607,  $c$  5.009 Å; U.C. 2; usually massive.  $H. = 5\text{--}5.5$ .  $G. = 7.78$ .

<sup>16</sup> M. J. Buerger: *Am. Mineral.*, XXXII, 411 (1947).

<sup>17</sup> A. Byström: *Ark. Kemi, Mineral. Geol.*, XIXB, No. 8 (1945).

<sup>18</sup> Wyckoff, R. W. G.: *Crystal Structures*, Sect. I (1948); W. Faber: *Zeit. Krist.*, LXXXIV, 408 (1933), gives a structure with lower symmetry.



F. = 2. Soluble in aqua regia. Opaque. Color pale copper red, with dark gray tarnish. Streak pale brownish black. Creamy pink in vertical reflected light. Polished surfaces strongly anisotropic and pleochroic. Uniaxial negative with  $N_O = 2.11$ ,  $N_E = 1.80$ ,  $N_O - N_E = 0.31$ , for  $\lambda = 589$ .<sup>19</sup> Reflection percentages<sup>3</sup> for O: red 59.5, orange 57.1, green 48.9; for E: red 58.5, orange 55.2, green 42.8. Found in veins with cobalt, silver, and copper ores, as at Natsume, Japan; Freiberg, Saxony; Cobalt, Ontario; etc.

**Covellite** (CuS) is dihexagonal dipyramidal with  $c/a = 4.3026$ ; space group<sup>20</sup>  $C6/mmc$ ;  $a$  3.802,  $c$  16.43 Å; U.C. 6; crystals horizontally striated with perfect basal cleavage; flexible in thin lamellae.  $H. = 1.5-2$ .  $G. = 4.6-4.76$ . Before the blow-pipe burns, giving off  $SO_2$ , and fuses at 2.5. Extremely thin plates translucent and pleochroic in light green tints with  $O > E$ . Uniaxial positive<sup>21</sup> with extreme dispersion and  $N_O < 1.0$  Li, 1.45 Na, 1.81 Tl. Opaque in ordinary thin section. Strongly anisotropic and pleochroic<sup>3</sup> in reflected light with  $O =$  deep blue (slightly violet),  $E =$  blue-white. Reflection percentages; red 10, orange 15, green 18.5. Luster submetallic, somewhat resinous. Found with other copper ores. Sometimes derived from the alteration of chalcocite. Found at Leogang, Austria; Butte, Montana; etc.

**CINNABAR** HEXAGONAL (TRIGONAL-TRAPEZOHEDRAL)  $c/a = 2.29$  HgS

**STRUC.**<sup>22</sup> Space group  $C3_12$  or  $C3_22$ ;  $a$  4.160,  $c$  9.540 Å; U.C. 3.

**PHYS. CHAR.** Crystals usually thick tabular or rhombohedral; also prismatic. Twinning on 0001. Perfect prismatic cleavage.  $H. = 2-2.5$ .  $G. = 8.1$ . Sublimes at 580° C. in the absence of oxygen.

**OPT. PROP.** Uniaxial positive with very high refringence, birefringence, and dispersion:  $N_O = 2.756$  (762 Å), 2.814 (672), 2.905 (598.5), 2.913 Na,  $N_E = 3.065$  (762 Å), 3.143 (672), 3.256 (598.5), 3.272 Na,  $N_E - N_O = 0.359$  Na. For  $N_O$ ,  $N_F - N_C = 0.4 \pm$ . Circular polarization produced  $-315^\circ$  for red. Luster adamantine. Streak scarlet. Color bright to brownish or grayish red.

**INVER.** Metacinnabarite is a rare isometric phase of HgS which is black and opaque. Space group  $F\bar{4}3m$ ;  $a$  5.854 Å.  $H. = 3$ .  $G. = 7.65$ . It is formed only from acid solutions; it changes to cinnabar under favorable conditions.

**OCCUR.** Chiefly in veins; also as a product of solfataric action about hot springs. It is often associated with pyrite, stibnite, realgar, calcite, quartz, barite, fluorite, etc. Found at Almaden, Spain; Ripa, Italy; New Almaden, California; etc.

**DIAG.** The optical properties, including color, are quite characteristic; also the volatility.

**REALGAR** MONOCLINIC PRISMATIC AsS

$$a:b:c = 0.6879:1:0.4858 \quad \beta = 106^\circ 32'$$

**STRUC.**<sup>23</sup> Space group  $P2_1/n$ ;  $a$  9.27,  $b$  13.50,  $c$  6.56 Å. U.C. 16.

**PHYS. CHAR.** Crystals short, prismatic, vertically striated, with distinct 010 cleavage.  $H. = 1.5-2$ .  $G. = 3.56$ . Fuses at 310° C. Wholly volatile. Soluble in alkalis.

<sup>19</sup> W. Faber: *Zeit. Krist.*, LXXXV, 223 (1933).

<sup>20</sup> H. S. Roberts and C. J. Ksanda: *Am. Jour. Sci.*, CCXVII, 489 (1929).

<sup>21</sup> H. E. Merwin: *Econ. Geol.*, X, 530 (1915).

<sup>22</sup> H. E. Buckley and W. S. Vernon: *Mineral. Mag.*, XX, 382 (1925).

<sup>23</sup> M. J. Buerger: *Am. Mineral.*, XX, 36 (1935).

**OPT. PROP.** The optic plane is 010;  $X \wedge c = -11^\circ$ . Inclined dispersion strong with  $r > v$ , very marked, giving abnormal interference colors near extinction.  $(- )2V = 49^\circ 34'$  (648),  $46^\circ 42'$  (589). For  $740 \text{ m}\mu$ ,<sup>24</sup>  $N_X = 2.458$ ,  $N_Y = 2.560$ ,  $N_Z = 2.578$ . For  $650 \text{ m}\mu$ ,  $N_X = 2.496$ ,  $N_Y = 2.617$ ,  $N_Z = 2.634$ . For  $590 \text{ m}\mu$ ,  $N_X = 2.538$ ,  $N_Y = 2.684$ ,  $N_Z = 2.704$ ,  $N_Z - N_X = 0.166$ . See Fig. 28.

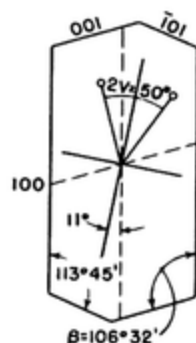


FIG. 28. The optic orientation of realgar.

Color and streak aurora red to orange yellow; pleochroic with  $X$  = nearly colorless to orange red,  $Y$  and  $Z$  = pale golden yellow to vermillion red.

**ALTER.** Changes on exposure to light to orpiment and arsenolite.

**OCCUR.** Found with silver and lead ores in veins; also in clay and slate; often produced by solfataric acid; also from geysers. Found at Nagyág, Rumania; Vesuvius, Italy; Mercur, Utah; etc.

**DIAG.** Distinguished from orpiment by its extinction angle and pleochroism, and from cinnabar by its negative biaxial character and pleochroism.

#### 4. Simple sulfides with type formula $A_2X_3$

**STIBNITE** ORTHORHOMBIC DIPYRAMIDAL  $Sb_2S_3$   
 $a:b:c = 0.9926:1:0.3393$

**STRUC.**<sup>25</sup> Space group  $Pbnm$ ;  $a$  11.20,  $b$  11.28,  $c = 3.83 \text{ \AA}$ . U.C. 4.

**PHYS. CHAR.** Crystals long prismatic, vertically striated, with perfect 010 cleavage.  $H. = 2$ .  $G. = (4.5-4.63)$ . M.P.  $546-551^\circ \text{ C}$ . Soluble in  $\text{HCl}$ .

**OPT. PROP.** Nearly opaque, but translucent to red and infrared rays. The optic plane is 100,  $Z = c$ . For  $760 \text{ m}\mu$ :  $(- )2V = 25^\circ 45'$ .  $N_X = 3.194$ ,  $N_Y = 4.046$ ,  $N_Z = 4.303$ ,  $N_Z - N_X = 1.109$ . Very strong dispersion.<sup>26</sup> Galena white in vertically reflected light. Strongly anisotropic and pleochroic with  $a$  = dull gray white,  $b$  = dull gray with olive

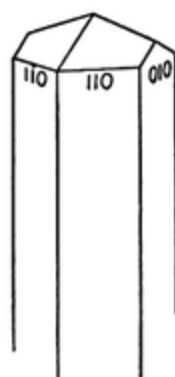


FIG. 29 A crystal habit of stibnite.

<sup>24</sup> O. Weigel: *Tsch. Min. Pet. Mit.*, XXXVIII, 288 (1925).

<sup>25</sup> W. Hofmann: *Zeit. Krist.*, LXXXVI, 225 (1933).

<sup>26</sup> A. Hutchinson (*Mineral. Mag.*, XIV, 199 (1909)) reports  $X = c$ , but also gives  $N_Z = 4.303$  for rays vibrating along the long axis. R. Bailly: *Acad. Roy. Belg. Bull.*, XXIV, 791 (1938), gives for  $852 \text{ m}\mu$ :  $Z = c$ ;  $N_Y = 3.875$ ,  $N_Z = 4.137$ . Orzel: *Bull. Soc. Fr. Min.*, LIII, 301, also reports  $Z = c$ . Berek (*Mit. Leitz Werke*, 63, 1, 1941) also gives  $Z = c$ , and  $N_Y = 4.44$ ,  $N_Z = 5.17$ , varying with the quality of the polish. E. P. T. Tyndall: *Phys. Rev.*, XXI, 162 (1923), gives  $N_1 = 4.7$  at  $660 \text{ m}\mu$ ,  $5.0$  at  $589$ ,  $5.5$  (max.) at  $510$ , and  $5.0$  at  $450$ ; also  $N_2 = 4.6$  at  $660$ ,  $4.5$  at  $589$ ,  $4.8$  (max.) at  $510$ , and  $4.4$  at  $450 \text{ m}\mu$ .



tint,  $c$  = pure white, very bright; reflection percentages <sup>3</sup>  $a$ , 32 red, 34.2 orange, 38.6 green;  $b$ , 24.9 red, 26.4 orange, 30.5 green;  $c$ , 35.4 red, 37.8 orange, 43.9 green.

Color and streak steel gray, subject to black tarnish. Luster metallic, often splendid.

ALTER. Oxidation of stibnite produces kermesite or valentinite.

OCCUR. Common in veins with sphalerite, galena, cinnabar, quartz, bornite, etc. Also found disseminated in limestone. Found at Pereta, Italy; Bau, Borneo; Hollister, California; etc.

DIAG. Opaque except in red light; extreme refringence and birefringence; vertically striated crystals of bright metallic luster.

## ORPIMENT

MONOCLINIC PRISMATIC

$As_2S_3$

$$a:b:c = 1.195:1:0.442 \quad \beta = 90^\circ 27'$$

STRUC.<sup>27</sup> Space group  $P2_1/n$ ;  $a$  11.47,  $b$  9.57,  $c$  4.24; U.C. 4.

PHYS. CHAR. Crystals small, with micaceous 010 cleavage; laminae flexible, inelastic.  $H. = 2$ .  $G. = 3.48$ . M.P.  $320^\circ C$ . Wholly volatile. Soluble in  $H_2SO_4$ .

OPT. PROP. The optic plane is near 001;  $X = b$ ,  $Y \wedge c = 1-3^\circ$  in acute angle  $\beta$ .  $(- )2V = 76^\circ$ ,  $r > v$  strong,<sup>28</sup>  $N_X = 2.4$  ca.  $Li$ ,  $N_Y = 2.81$ ,  $N_Z = 3.02$ ,  $N_Z - N_X = 0.62$  ca. Color and streak lemon yellow. Pleochroic in thick plates in yellow tints with  $X > Y$  and  $Z$ ;  $Y =$  yellow,  $Z =$  greenish yellow.

OCCUR. Found in hot spring and geyser deposits, in veins, and in deposits from volcanic gases. Also formed by sublimation in burning coal mines. A common artificial product, sometimes called king's yellow. Found at Vesuvius, Italy; Balin, Asia Minor; Mercur, Utah; etc.

DIAG. The micaceous cleavage, yellow color, volatility, and extreme birefringence are characteristic.

**Kermesite** ( $Sb_2S_2O$ ) is monoclinic prismatic with<sup>29</sup>  $a:b:c = 1.339:1:1.265$ ,  $\beta = 101^\circ 45'$  ( $C2/m$ ,  $a$  10.97,  $b$  8.19,  $c$  10.36). Crystals acicular parallel to  $b$  with perfect 001 and distinct 100 cleavages. Sectile.  $H. = 1-1.5$ .  $G. = 4.5$ .  $F. = 517^\circ$ . Volatile.  $Z$  parallel to elongation ( $b$ );  $(+)2V =$  small,  $N_X > 2.72$ ,  $N_Y = 2.74$ ,  $N_Z = ?$ ,  $N_Z - N_X =$  extreme. Absorption weak,  $X > Y > Z$ . Color cherry red. Streak brownish red. Alteration product of stibnite.

## 5. Simple sulfides with type formula $AX_2$

### PYRITE

ISOMETRIC DIPLOIDAL

$FeS_2$

STRUC.<sup>30</sup> Space group  $Pa\bar{3}$ ;  $a$  5.405 Å. U.C. 4.

COMP. In rare cases Ni may replace Fe to at least 60% (atomic), then  $a$  5.57. With 35% Ni,  $G. = 4.82$ .

<sup>27</sup> M. J. Buerger: *Am. Mineral.*, XXVII, 301 (1942).

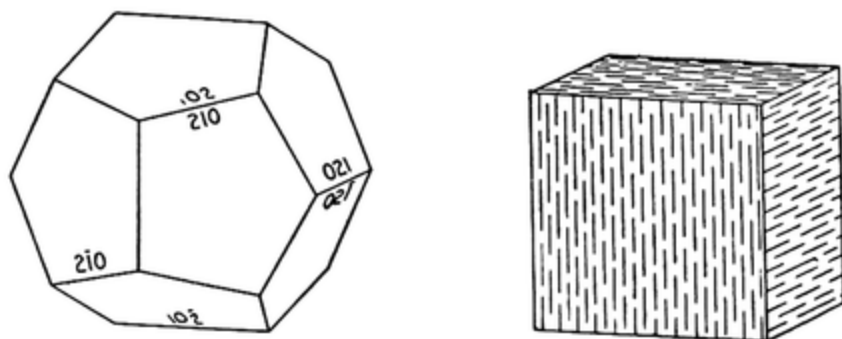
<sup>28</sup> E. S. Larsen and H. Berman: *U. S. Geol. Surv. Bull.* 848, 213 (1934).

<sup>29</sup> C. W. Wolfe: *Dana's Syst. Mineral.*, 7th Ed., I, 279 (1944).

<sup>30</sup> H. M. Parker and W. J. Whitehouse: *Phil. Mag.*, XIV, 939 (1932).

**PHYS. CHAR.** Crystals commonly cubes, pyritohedrons, or octahedrons; faces often striated parallel to the edge (100):(210). See Figs. 30, 31. Twinning usually by penetration with  $a$  as the twinning axis.  $H. = 6-6.5$ .  $G. = 5.02$ .  $M.P. 642^{\circ} C$ . In the closed tube gives a sulfur sublimate and a magnetic residue. Burns with a blue flame. Insoluble in  $HCl$ ; decomposed by  $HNO_3$ .

**OPT. PROP.** Opaque. Luster metallic. Color pale brass yellow. Streak greenish to brownish black. Creamy white in vertically reflected light. Polishes with difficulty and in relief on account of hardness. Reflection percentages: <sup>3</sup> red 52.5, orange 53.5, green 54.



FIGS. 30, 31. Crystal forms of pyrite.

**ALTER.** Pyrite loses sulfur and changes to pyrrhotite at  $665^{\circ} C$ . (beginning at  $575^{\circ} C$ ). This reaction is reversed at  $550^{\circ} C$ . in the presence of available sulfur. Pyrite alters in nature quite readily; the process may be one chiefly of oxidation, or it may be largely hydration. In the first case the product is hematite, or, more commonly, limonite or goethite. In the second case the product is chiefly melanterite, sometimes mixed with copiapite, gypsum, halotrichite, etc. The alteration of pyrite usually results not only in the formation of new iron minerals but also in the production of free sulfuric acid; therefore altered pyrite is often accompanied by various other sulfates formed by the action of this free acid on surrounding minerals. Gypsum is very commonly produced in this way; in other cases the product may be alunogen, halotrichite, or still other sulfates.

**OCCUR.** Pyrite occurs under many varying conditions; it is one of the most widely distributed of minerals. Thus, it is formed in many igneous rocks, usually in very small amount; it occurs in various metamorphic rocks likewise in small amount; it is found in some purely sedimentary rocks, in some cases being evidently of contemporaneous origin, but more frequently being deposited in the rock at a later date; finally, it is found often in abundance in many ore deposits and hot-spring deposits. Pyrite forms artificially from alkaline solutions of moderate temperatures or at high temperatures under pressure; it also forms from acid solutions.

**DIAG.** Pyrite is distinguished from many opaque minerals by the pale brass yellow color and metallic luster; distinguished from chalcopyrite by paler color and greater hardness, giving poorer polish. Pyrrhotite has a pale bronze yellow color, is softer than pyrite, and is readily attacked by HCl. Pyrite is difficult to distinguish from marcasite in the absence of crystal form, but marcasite has a slightly paler color, a lower density, and alters more readily.

**Hauerite** ( $MnS_2$ ) is isometric diploidal; <sup>31</sup> space group  $Pa\bar{3}$ ;  $a$  6.095 Å, U.C. 4; often in octahedrons with distinct cubic cleavage.  $H. = 4$ .  $G. = 3.46$ .  $F. = 3$ . Soluble in HCl. Isotropic and deep red in section with  $N = 2.69$  Li; 2.634 for  $\lambda = 8521$  Å.<sup>32</sup> Color reddish brown to brownish black. Streak brownish red. Found in clay and schist as at Raddusa, Sicily; Big Hill, Texas; etc.

**MOLYBDENITE**      DIHEXAGONAL DIPYRAMIDAL       $c/a = 3.815$        $MoS_2$

**STRUC.**<sup>33</sup> Space group  $C6/mmc$ ;  $a$  3.15,  $c$  12.30 Å. U.C. 2.

**PHYS. CHAR.** Crystals basal plates or short prismatic, with perfect basal cleavage; laminae flexible, inelastic.  $H. = 1-1.5$ .  $G. = 4.92$ ; 5.06 (artificial). M.P. 1185° C. Decomposed by  $HNO_3$ .

**OPT. PROP.** Opaque. Luster metallic. Color lead gray. Streak slightly greenish (on glazed porcelain). Transparent to infrared<sup>32</sup> and uniaxial negative with  $N_O = 4.336$  and  $N_E = 2.035$  for  $\lambda = 852$  mμ. Also <sup>34</sup>  $N_O = 5.23$  (max.) at 620 mμ, 4.9 at 655, and 4.7 (min.) at 595 mμ. Optically negative. Grayish white in vertically reflected light. Reflection percentages<sup>3</sup> for O: red 30.5, orange 31.5, green 36; and for E: red 15, orange 18, green 15.5.

**ALTER.** Changes easily to molybdenite.

**OCCUR.** Found embedded or disseminated in crystalline limestone, gneiss, vein quartz, granite, etc. Localities include Telemarken, Norway; Haddam, Connecticut; Gibson, California; etc.

**MARCASITE**      ORTHORHOMBIC DIPYRAMIDAL       $FeS_2$   
 $a:b:c = 0.8194:1:0.6245$

**STRUC.**<sup>35</sup> Space group  $Pn\bar{m}$ ;  $a$  4.436,  $b$  5.414,  $c$  3.381 Å. U.C. 2.

**PHYS. CHAR.** Crystals {010} tablets or pyramidal. More commonly in masses with radiating or fibrous texture. Twinning on 101, sometimes repeated; twinning on 011 less common. Distinct 101 cleavage.  $H. = 6-6.5$ .  $G. = 4.887$ . On charcoal burns with sulfurous odor. Decomposed by  $HNO_3$ .

**OPT. PROP.** Opaque. Color pale bronze yellow, darkening on ex-

<sup>31</sup> W. Biltz and F. Wiechmann: *Zeit. anorg. Chem.*, CCXXVIII, 268 (1931).

<sup>32</sup> R. Bailly: personal communication, Dec. 30, 1947. See *Am. Mineral.*, XXXIII, 519 (1948).

<sup>33</sup> R. G. Dickinson and L. Pauling: *J. Am. Chem. Soc.*, XLV, 1465 (1923).

<sup>34</sup> E. P. T. Tyndall: *Phys. Rev.*, XXI, 162 (1923). In the ultraviolet A. W. Mayer (*Phys. Rev.*, XXVII, 247, 1926) gives for  $MoS_2$ :  $N = 7.8$  (max.) at 480 and 2.7 (min.) at 330 mμ.

<sup>35</sup> M. J. Buerger: *Am. Mineral.*, XXII, 48 (1937); *Zeit. Krist.*, XCVII, 504 (1937).

posure. Streak grayish or brownish black. Luster metallic. Polishes with difficulty and in relief. Creamy white in vertically reflected light. Produces marked rotation of the plane of polarization of reflected light. Strongly anisotropic and pleochroic with  $a$  = creamy white,  $b$  = light yellowish white,  $c$  = white with rose-brown tint. Reflection percentages: <sup>3</sup> red 44.5, orange 45.5, green 52.

INVER. Changes to pyrite very slowly at 450° C.; more rapidly at 525° C.

ALTER. Alters by oxidation much more rapidly than pyrite and gives rise to melanterite, or, less commonly, copiapite. At the same time free sulfuric acid is produced, which is an active agent in some of the processes of secondary sulfide enrichment of ore deposits. At other times marcasite alters to limonite or goethite or hematite, sometimes with the production of free sulfur.

OCCUR. Abundant in coal beds; in metalliferous veins in all kinds of rocks with copper, lead, zinc, etc.; in veins and disseminations in limestones. Forms only from acid solutions at temperatures below 450° C. Found at Teplitz, Bohemia; Kent, England; Guanojuato, Mexico; Mineral Point, Wisconsin; etc.

**ARSENOPYRITE** (*Mispickel*)      MONOCLINIC PRISMATIC      FeAsS  
 $a:b:c = 1.683:1:1.136$        $\beta = 90^\circ$

STRUC. Space group <sup>36</sup>  $P2_1/c$ ;  $a$  9.51,  $b$  5.65,  $c$  6.42 Å; U.C. 8.

PHYS. CHAR. Crystals prismatic or modified with distinct 101 cleavage. Twinning as in marcasite.<sup>37</sup> H. = 5.5–6. G. = 5.9–6.2. F. = 2 to a magnetic globule. Strikes fire with steel giving a garlic odor. Decomposed by HNO<sub>3</sub>.

OPT. PROP. Opaque. Color silver white, sometimes grayish. Luster metallic. Streak dark grayish black. White color in vertically reflected light. Malmqvist<sup>38</sup> has calculated the refractive indices, as follows:

<sup>36</sup> M. J. Buerger: *Am. Mineral.*, XXII, 48 (1937); also M. J. Buerger: *Zeit. Krist.*, XCV, 83 (1936).

<sup>37</sup> J. S. Lukesh: *Am. Mineral.*, XXV, 619 (1940).

<sup>38</sup> D. Malmqvist: *Bull. Geol. Inst. Upsala*, XXVI, 1 (1937). If the indices given are correct, arsenopyrite must be even more complicated than lithiophilite in the variations of optic angle and optic plane. Indeed, at  $\lambda = 656$  it must be biaxial and positive with  $2V = 35^\circ \pm$  and the optic plane parallel with 100; it is uniaxial positive at about  $\lambda = 645$  and then the optic plane becomes 010; the optic angle increases to  $90^\circ$  at  $\lambda = 600$  and then the optic sign becomes negative and the optic angle decreases to  $0^\circ$  at  $\lambda = 575$ ; then the optic plane becomes 001 and the optic angle increases to  $90^\circ$  at about  $\lambda = 562$ ; then the sign becomes positive and the optic angle decreases to zero at about  $\lambda = 547$ ; then the optic plane becomes parallel with 100 once again and the optic angle increases to about  $95^\circ$  at  $\lambda = 527$ , changing sign again at about  $\lambda = 532$ .

$N \parallel a = 1.847$  red, 1.597 yellow, 1.404 green,  $N \parallel b = 1.830$  red, 1.660 yellow, 1.490 green,  $N \parallel c = 1.994$  red, 1.573 yellow, 1.307 green. See Fig. 33. Reflection percentages:<sup>3</sup> red 47, orange 48.5, green 57.5. Orce<sup>39</sup> reports for white light:  $X = a$ ,  $Y = b$ ,  $Z = c$ .

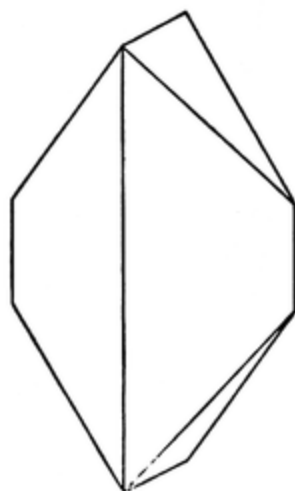


FIG. 32. A crystal habit of arsenopyrite.

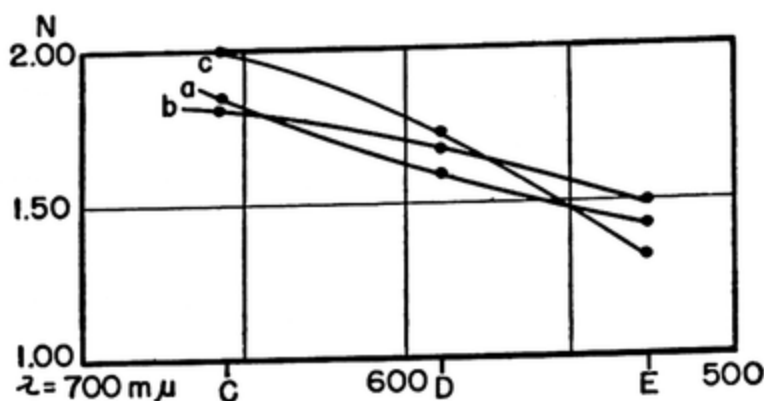


FIG. 33. Refractive indices of arsenopyrite.

**OCCUR.** Found especially in veins, commonly associated with ores of silver, lead, tin, gold, as at Homestake, South Dakota; Cornwall, England; Meymac, France; Asio, Japan; etc.

## B. MULTIPLE SULFIDES (OR "SULFOSALTS")

### 1. Multiple sulfides with type formula $A_m B_n X_p$ and $(m + n):p > 1:1$

<b>GRAY COPPER</b>	<b>ISOMETRIC HEXTETRAHEDRAL</b>	$\text{Cu}_{10}(\text{Zn,Fe,Cu})_2(\text{As,Sb})_4\text{S}_{13}$
<b>Tennantite</b>		$\text{Cu}_{10}(\text{Zn,Fe,Cu})_2\text{As}_4\text{S}_{13}$
<b>Tetrahedrite</b>		$\text{Cu}_{10}(\text{Zn,Fe,Cu})_2\text{Sb}_4\text{S}_{13}$

**STRUC.**<sup>40</sup> Space group  $I\bar{4}3m$ ;  $a$  10.19 (tennantite) to 10.33 Å (tetrahedrite); U.C. 2.  
**COMP.** There is a complete series from the As to the Sb compound; Bi may be present; also Ag, Hg, and perhaps Pb.

**PHYS. CHAR.** Crystals tetrahedral, often modified. Twinning on 111 or, rarely, on 100. Cleavage none.  $H. = 3-4.5$  (tennantite harder).  $G. = 4.6$  (tennantite) to 5.0 (tetrahedrite), and to 5.4 with Hg and Pb. See Fig. 34.  $F. = 1.5$ . Decomposed by  $\text{HNO}_3$ .

**OPT. PROP.** Opaque to translucent in red (tennantite). For<sup>41</sup>  $\lambda = 8521 \text{ Å}$ ;  $N = 2.914$  to 3.128, probably increasing with increase of Sb. Color gray to iron black, rarely purple. Streak gray to brown or red. Luster metallic, often splendent.

<sup>39</sup> J. Orce: *Bull. Soc. Fr. Min.*, LIII, 301 (1930).

<sup>40</sup> F. Machatschi: *Zeit. Krist.*, LXVIII, 204<sup>v</sup> (1928).

<sup>41</sup> R. Bailly: *Bull. Soc. Fr. Min.*, LXX, 49 (1948).

Gray to olive brown in vertically reflected light. Reflection percentages<sup>3</sup> for tennantite: 21.5 red, 24 orange, 29.5 green, and for tetrahedrite: 20.5 red, 24 orange, 27 green.

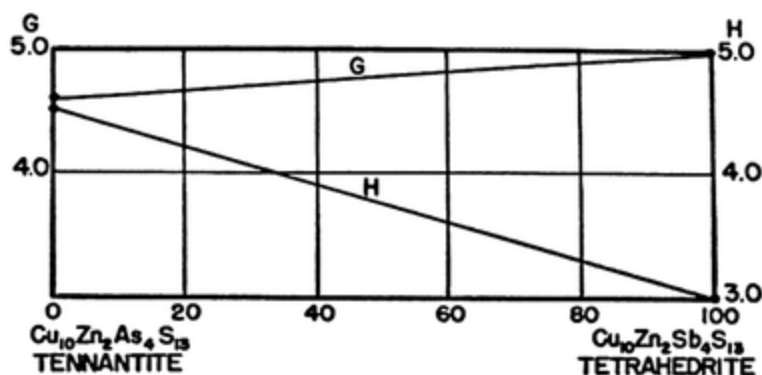


FIG. 34. Properties of gray copper.

**OCCUR.** Found chiefly in veins with other copper ores, and with pyrite, galena, sphalerite, and various silver and gold ores, as at Freiberg, Saxony; Cabrière, France; Liskeard, Cornwall, England; Bingham, Utah; etc.

## RUBY SILVER

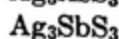
### DITRIGONAL PYRAMIDAL



**Proustite**  $c/a = 0.804$



**Pyrargyrite**  $c/a = 0.789$



**STRUC.**<sup>42</sup> Space group  $R3c$ ;  $a$  10.74,  $c$  8.64 Å (proustite) to  $a$  11.04,  $c$  8.71 Å (pyrargyrite). Hexagonal U.C. 6.

**COMP.** Natural crystals are usually nearly pure  $\text{Ag}_3\text{AsS}_3$  or  $\text{Ag}_3\text{SbS}_3$ , and ruby silver may be two minerals, but the two compounds are miscible in all proportions<sup>43</sup> in crystals at temperatures near fusion.

**PHYS. CHAR.** Crystals prismatic to rhombohedral, hemimorphic, small, often modified. Usually massive, compact. Twinning common on  $10\bar{1}4$ , rare on  $10\bar{1}1$ . Distinct rhombohedral cleavage.  $H. = 2-2.25$ .  $G. = 5.51$  (proustite) to 5.85 (pyrargyrite). See Fig. 35. Easily fusible. Decomposed by  $\text{HNO}_3$ .

**OPT. PROP.** Color scarlet (proustite), to black (pyrargyrite). Streak red. Luster adamantine. Bluish to grayish white in vertically reflected light. Uniaxial negative with  $N_O = 2.9789$  Li, 3.0877 Na,  $N_E = 2.7113$  Li, 2.7924 Na,  $N_O - N_E = 0.2676$  Li, 0.2953 Na for proustite and  $N_O = 3.084$  Li,  $N_E = 2.881$ ,  $N_O - N_E = 0.203$  for pyrargyrite. See Fig. 35. Deep red by transmitted light, and pleochroic with  $O = \text{blood red}$  and  $E = \text{cochineal red}$ . Reflection percentages<sup>44</sup> for proustite; red 20.5, orange 21.5, green 28; for pyrargyrite: red 24.5, orange 27, green 32.5.

**OCCUR.** Found in veins with other silver ores and with galena, sphalerite, tetrahedrite, etc., as at Příbram, Bohemia; Chañarcillo, Chile; Austin, Nevada; Cobalt, Ontario; etc.

**Stephanite** ( $\text{Ag}_5\text{SbS}_4$ ) is orthorhombic with  $a:b:c = 0.629:1:0.685$ . Crystals usually prismatic or  $\{001\}$  tablets. Poor 010 cleavage.  $H. = 2-2.5$ .  $G. = 6.2-6.3$ . Opaque with metallic luster. For  $\lambda = 8521$ :  $X = c$ ,  $Y = b$ ,  $(- )2V = 67^\circ$ ,  $N_X =$

<sup>42</sup> D. Harker: *J. Chem. Phys.*, IV, 381 (1936).

<sup>43</sup> F. M. Jaeger and H. S. van Klooster: *Zeit. anorg. Chem.*, LXXVIII, 245 (1912).

<sup>44</sup> R. Bailly: personal communication, Dec. 30, 1947. See ref. 41.



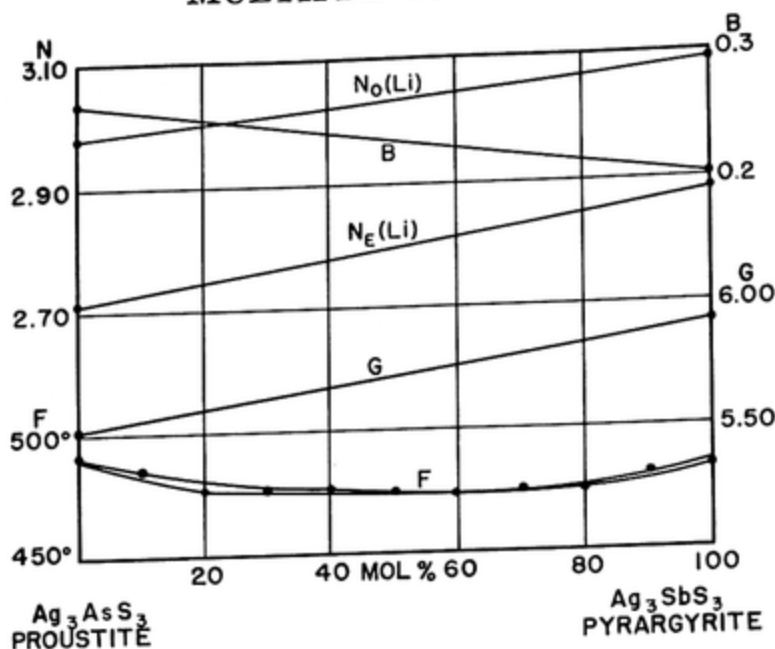


FIG. 35. Properties of ruby silver.

3.001,  $N_Y = 3.053$ ,  $N_Z = 3.077$ ,  $N_Z - N_X = 0.076$ . Found in silver ore deposits as at the Comstock Lode, Nevada.

## ENARGITE

ORTHORHOMBIC PYRAMIDAL



$$a:b:c = 0.8713:1:0.8277$$

STRUC.<sup>45</sup> Space group  $Pnm$ ;  $a$  6.46,  $b$  7.43,  $c$  6.18 Å. U.C. 2.

PHYS. CHAR. Crystals prismatic and vertically striated with perfect 110 cleavage.  $H. = 3$ .  $G. = 4.44$ .  $F. = 1$ . Soluble in  $\text{HNO}_3$ .

OPT. PROP. The optic plane<sup>32</sup> is 010;  $Z = c$ ;  $(+ )2V = 54^\circ$ ;  $N_X = 3.081$ ,  $N_Y = 3.089$ ,  $N_Z = 3.120$ ,  $N_Z - N_X = 0.039$ . Opaque. Color and streak grayish black. Luster metallic, but tarnishing dull. Gray to light brown in vertically reflected light. Strongly anisotropic with weak pleochroism; produces marked rotation of the plane of polarization of reflected light. Reflection percentages:<sup>3</sup> red 21.5, orange 21.5, green 23.

OCCUR. Important at some copper mines, as at Bor, Serbia, Cerro de Pasco, Peru, and Butte, Montana.

**Pyrostilpnite** ( $\text{Ag}_3\text{SbS}_3$ ) is monoclinic prismatic with  $a:b:c = 0.355:1:0.178$ ,  $\beta = 90^\circ 0'$ . Crystals {010} tablets with perfect 010 cleavage.  $H. = 2$ .  $G. = 5.94$ .<sup>46</sup>  $F. = 1$ . The optic plane is 010;  $X \wedge c = 8^\circ$ . Refractive indices very high. Color hyacinth red. Streak orange-yellow. Luster adamantine. Found with ruby silver, as at Příbram, Bohemia.

**Xanthoconite** ( $\text{Ag}_3\text{AsS}_3$ ) is monoclinic prismatic with  $a:b:c = 1.919:1:1.015$ ,  $\beta = 91^\circ 13'$ . Crystals {001} tablets with distinct 001 cleavage.  $H. = 2-3$ .  $G. = 5.4-5.6$ .  $F. = 1$ . The optic plane and  $Z$  are normal to 010;  $X$  near  $c$ .  $(- )2E = 125^\circ \pm$ ,  $r < v$  marked.  $N$  near 3;  $N_Z - N_X = \text{extreme}$ . Color cochineal red to

<sup>45</sup> L. Pauling and S. Weinbaum: *Zeit. Krist.*, LXXXVIII, 48 (1934).

<sup>46</sup> C. Palache, H. Berman, and C. Frondel: *Dana's Syst. Mineral.*, 7th Ed., I (1944)



orange or clove brown. Streak orange-yellow. Adamantine luster. Found usually with ruby silver, as at Ouray, Colorado.

**POLYBASITE**

## MONOCLINIC PRISMATIC



$$a:b:c = 1.7309:1:1.5796 \quad \beta = 90^\circ \text{ ca.}$$

STRUC.<sup>47</sup> Space group  $C2/m(?)$ ;  $a$  26.12,  $b$  15.08,  $c$  23.88 kX. U.C. 16.

COMP. Copper may proxy for silver at least to 30 atomic per cent. Arsenic may proxy for antimony at least to 60 atomic per cent.

PHYS. CHAR. Crystals six-sided tabular prisms; twinning on 110 common. Imperfect basal cleavage. Very brittle.  $H. = 2-3$ .  $G. = 6.3$ .  $F. = 1$  with spurting. Decomposed by  $\text{HNO}_3$ .

OPT. PROP. The optic plane is 100;  $X = c$ .  $(- )2E = 70^\circ \pm$ ,  $N_Y = 2.72$  Li,  $N_Z - N_X =$  very strong. Produces marked rotation of the plane of polarization of reflected light. Color and streak black; cherry red in thin section. Grayish white in vertically reflected light. Reflection percentages: <sup>3</sup> red 25.5, orange 25.5, green 29.5.

OCCUR. Found in veins with silver and copper ores, as at Příbram, Bohemia; Atacama, Chile; Arizpe, Mexico; Aspen, Colorado; Cobalt, Ontario.

## 2. Multiple sulfides with type formula $A_mB_nX_p$ and $(m + n):p = 1:1$

**Trechmannite** ( $\text{AgAsS}_2?$ ) is hexagonal rhombohedral with  $c/a = 0.653$ ; crystals small prismatic with rhombohedral and basal cleavages.  $H. = 1.5-2$ . Uniaxial negative with  $N_O = 2.6$  Li,  $N_E = ?$ ,  $N_O - N_E =$  extreme, color and streak scarlet; pleochroic with  $O =$  pale red,  $E =$  nearly colorless. On heating inverts to a biaxial phase, probably smithite, on which Larsen<sup>48</sup> found:  $(- )2V =$  moderate,  $N_X = 2.48$  Li,  $N_Y = 2.58$ ,  $N_Z = 2.60$ ,  $N_Z - N_X = 0.12$ . Trechmannite occurs in dolomite in the Binnenthal, Switzerland.

**BOURNONITE**

## ORTHORHOMBIC DIPYRAMIDAL



$$a:b:c = 0.938:1:0.897$$

STRUC.<sup>48</sup> Space group  $Pnmm$ ;  $a$  8.10,  $b$  8.65,  $c$  7.75 Å. U.C. 4.

PHYS. CHAR. Crystals short prismatic to tabular, often twinned on 110.  $H. = 2.5-3$ .  $G. = 5.8-5.9$ .  $F. = 1$ . Decomposed by  $\text{HNO}_3$ .

OPT. PROP. Opaque. Color and streak steel gray. Luster bright metallic. For  $\infty$   $\lambda = 8521$  Å,  $X = a$ ,  $Y = b$ ,  $(+)2V = 52^\circ$ ,  $N_X = 3.141$ ,  $N_Y = 3.166$ ,  $N_Z = 3.280$ ,  $N_Z - N_X = 0.139$ . White in vertically reflected light; weak pleochroism and anisotropism. Reflection percentages: <sup>3</sup> red 29, orange 30, green 33.5.

OCCUR. Found in hydrothermal deposits in veins with galena, tetrahedrite, stibnite, chalcopyrite, pyrite, etc., as at Neudorf, Germany; Kapnik, Rumania; Park City, Utah; etc.

**Hutchinsonite**  $[(\text{Pb},\text{Cu})_2(\text{Cu},\text{Ag})\text{As}_5\text{S}_{10}]$  is orthorhombic with <sup>46</sup>  $a:b:c = 0.612:1:0.462$ . Crystals flattened prisms, complex, with distinct 010 cleavage.  $H. = 1.5-2$ .  $G. = 4.6$ . The optic plane is 010;  $X = a$ .  $(- )2V = 19^\circ 44'$  C,  $37^\circ 34'$  Na,  $r < v$  extreme.  $N_X = 2.779$  C, 3.078 D,  $N_Y = 3.063$  C, 3.176 D,  $N_Z = 3.073$  C, 3.188 D,  $N_Z - N_X = 0.110$  D. Color and streak scarlet to ver-

<sup>47</sup> M. A. Peacock and L. G. Berry: *Mineral. Mag.*, XXVIII, 1 (1947).

<sup>48</sup> I. Oftedal: *Zeit. Krist.*, LXXXIII, 157 (1932).

milium; pleochroism weak. Adamantine luster. Reflection percentage: <sup>3</sup> orange 29. Found in dolomite at Lengenbach, Switzerland.

**Smithite** ( $\text{AgAsS}_2$ ) is monoclinic prismatic with  $a:b:c = 2.221:1:1.957$ ,  $\beta = 101^\circ 12'$ ; space group  $A2/a$  or  $Aa$ ,<sup>49</sup>  $a$  17.20,  $b$  7.76,  $c$  15.16 Å. U.C. 24; crystals {100} plates, apparently hexagonal with perfect 100 cleavage.  $H. = 1.5-2$ .  $G. = 4.88$ . The optic plane<sup>50</sup> is 010;  $Z \wedge c = -4^\circ$  Li and  $-6.5^\circ$  Na.  $(- )2V = 65^\circ$ ,  $N'_X = 3.18$ ,  $N_Y = 3.27$  ca.,  $N'_Z = 3.36$ ,  $N'_Z - N'_X = 0.18$ . (See also trechmannite.) Color and streak vermilion altering to orange-red on exposure. Luster adamantine. Found in the Binnenthal, Switzerland.

**Miargyrite** ( $\text{AgSbS}_2$ ) is monoclinic prismatic with  $a:b:c = 2.994:1:2.909$ ,  $\beta = 98^\circ 37'$ ; space group<sup>51</sup>  $C2/c(?)$ ;  $a$  13.17,  $b$  4.39,  $c$  12.83 Å. U.C. 8. Crystals small tabular or prismatic with poor 010 cleavage.  $H. = 2-2.5$ .  $G. = 5.2$ .  $F. = 1$ . Decomposed by  $\text{HNO}_3$ . Nearly opaque.  $(+ )2V = \text{moderate}$ ,  $N_X > 2.72$  Li,  $N_Z - N_X = \text{very strong}$ . Color iron black; streak cherry red; deep blood red in thin section, with distinct absorption. Bluish white in vertically reflected light. Found in ore deposits, as at Randsburg, California.

**Lorandite** ( $\text{TlAsS}_2$ ) is monoclinic prismatic with  $a:b:c = 1.087:1:0.539$ ,  $\beta = 104^\circ 16'$ ; space group<sup>46,52</sup>  $P2_1/x$  or  $P2/x$ ;  $a$  12.25,  $b$  11.32,  $c$  6.10 Å. U.C. 8. Crystals tabular or prismatic highly modified. Perfect 100 and distinct  $\bar{2}01$  cleavages.  $H. = 2-2.5$ .  $G. = 5.53$ .  $F. = 1$ . Volatile. Soluble in  $\text{HNO}_3$ . The optic plane and  $Z$  normal to 010;  $X$  nearly  $= a$ .  $2V$  large, probably positive. Elongation of cleavage fragments positive.  $N_X > 2.72$  Li,  $N_Z - N_X = \text{extreme}$ . Color cochineal red; streak cherry red. Weakly pleochroic with  $Y = \text{purple red}$ ,  $Z = \text{orange red}$ . Gray in vertically reflected light. Reflection percentages: <sup>3</sup> red 20, orange 23, green 29.5. Found on realgar in Macedonia, and at the Rambler mine in Wyoming.

### 3. Multiple sulfides with type formula $A_mB_nX_p$ and $(m + n):p < 1:1$

**Dufrenoyite** ( $\text{Pb}_2\text{Sb}_2\text{S}_5$ ) is monoclinic prismatic<sup>46</sup> with  $a:b:c = 0.651:1:0.613$ ,  $\beta = 90^\circ 34'$ . Crystals {010} tablets with perfect 010 cleavage.  $H. = 3$ .  $G. = 5.53$ .  $N > 2.72$  with very strong birefringence. Color gray; streak reddish brown; luster metallic. Dark red in transmitted light. White in vertically reflected light, with deep red internal reflections. Weak pleochroism. Found in dolomite at Imfeld, Switzerland; Dundas, Tasmania; and elsewhere (?).

**Livingstonite** ( $\text{HgSb}_4\text{S}_7$ ) is monoclinic prismatic with  $a:b:c = 3.757:1:5.366$ ,  $\beta = 94^\circ 10'$ ; space group<sup>53</sup>  $P2_1/c$ ;  $a$  15.14,  $b$  3.98,  $c$  21.60 Å. U.C. 4. Crystals needles elongated along  $b$ , with perfect basal cleavage.  $H. = 2$ .  $G. = 4.81$ .  $F. = 1$ . Volatile. Biaxial, probably negative:  $Z = b$ .  $N_X > 2.72$ ,  $N_Y = 3$  ca.,  $N_Z = ?$ ,  $N_Z - N_X = \text{extreme}$ . Nearly opaque. Color lead gray; streak red. Luster adamantine to metallic. Microscopic prisms are red with slight absorption,  $X > Z$ . White in vertically reflected light with deep red internal reflections. Reflection percentages: <sup>3</sup> red 30, orange 32.5, green 37. Found at Huitzuc and Guadalcázar, Mexico, with sulfur, cinnabar, etc.

<sup>49</sup> M. A. Peacock: *Univ. Toronto Geol. Stud.*, L, 81 (1945).

<sup>50</sup> Smith and Prior: *Mineral. Mag.*, XIV, 283 (1907).

<sup>51</sup> W. Hofmann: *Sitzb. P. Akad. Wiss.*, LV, 111 (1938).

<sup>52</sup> W. Hofmann: *Fortsch. Min., Krist., Pet.*, XVII, 46 (1932). The glide component  $x = \frac{1}{2}(a + 2c)$  is simply  $\frac{1}{2}a$  in Hofmann's original setting, with  $a$  15.02,  $\beta$   $127^\circ 45'$ , and space group  $P2/a$  or  $P2_1/a$ .

<sup>53</sup> W. E. Richmond: *Am. Mineral.*, XXI, 719 (1936).

## IV. OXIDES

As in the case of the halides and sulfides, both simple oxides<sup>1</sup> and multiple oxides are recognized. It is convenient to treat hydroxides separately. The arrangement is according to decreasing A to X ratio in the simple oxides and decreasing (A + B) to X ratio in the multiple oxides. An outline classification follows:

### A. Simple Oxides.

1. Type formula  $A_2X$ .
2. Type formula  $AX$ .
3. Type formula  $A_2X_3$ .
4. Type formula  $AX_2$ .
5. Type formula  $AX_3$ .

### B. Hydroxides.

1. Type formula  $AX_2$ .
2. Type formula  $AX_3$ .

### C. Multiple Oxides.

1. Type formula  $ABX_2$ .
2. Type formula  $AB_2X_4$ .
3. Type formula  $A_mB_nX_p$  and  $(m + n):p = 2:3$ .
4. Type formula  $A_mB_nX_p$  and  $(m + n):p = 1:2$ .

## A. SIMPLE OXIDES

### 1. Simple oxides with type formula $A_2X$

#### CUPRITE

ISOMETRIC (HEXOCTAHEDRAL)

$Cu_2O$

STRUC.<sup>2</sup> Space group  $Pn3m$ ;  $a$  4.25 Å. U.C. 2.

PHYS. CHAR. Crystals commonly octahedrons; also cubes and dodecahedrons, often much modified. Also capillary (*chalcotrichite*). Octahedral cleavage indis-

<sup>1</sup> Oxides are considered "simple" if they contain only one metal, or two or more metals whose ions are near enough in size to occupy equivalent positions in the crystal structure.

<sup>2</sup> M. C. Neuberger: *Zeit. Krist.*, LXXVII, 169 (1931).

tinct.  $H. = 3.5-4$ .  $G. = (5.85-6.15)$ . Fusible, giving green flame color. Soluble in pure  $H_2SO_4$ . Streak red.

OPT. PROP. Isotropic with  $N = 2.849$  (red). Color in mass red, usually cochineal red; in thin section red (to yellow, with decreasing thickness); in polished section bluish white with blood red internal reflections, showing anomalous anisotropism and pleochroism. Reflection percentages: <sup>3</sup> red 21.5, orange 22.5, green 30. Again: white <sup>4</sup> 29.5.

ALTER. Malachite is the commonest product of alteration; also native copper, azurite, or chrysocolla. Cuprite itself is a product of alteration of copper sulfide ores.

OCCUR. Found usually in veins and confined to the upper oxidized portion, as at Siegen, Westphalia; Redruth, Cornwall, England; Bisbee, Arizona; etc. Also in cavities or somewhat disseminated, as at Chessy, France.

DIAG. Distinguished from other red minerals by the isotropic character.

## ICE

## DIHEXAGONAL PYRAMIDAL

$$c/a = 0.942$$



Unlike other compounds,  $H_2O$  has three different names, depending upon its condition: as a solid it is called *ice*; as a liquid it is *water*; as a gas it is *steam* or *aqueous vapor*. For present purposes ice is the most important state.

STRUC.<sup>5</sup> Space group  $C6mc(?)$ ;  $a$  7.82,  $c$  7.36; hexagonal U.C. 12.

PHYS. CHAR. Complete crystals rare; often in skeleton crystals (*snow*) of hexagonal symmetry. Usually basal tablets; also granular massive. Basal gliding developed by pressure.  $H. = 1.5$  (at about  $5^\circ C.$ ;  $H. = 4$  at  $-44^\circ$ , and 6 at  $-78.5^\circ$ ).<sup>6</sup>  $G. = 0.918$ . Melts to *water* at  $0^\circ C.$ , which becomes *steam* at  $100^\circ C.$  (and 760 mm. pressure).

OPT. PROP. Uniaxial positive. Refrindex lower than that of almost any other mineral; birefringence very weak. Colorless to white; pale blue in thick masses. At about  $-3^\circ C.$ ,  $N_O = 1.3069$  Li, 1.3091 Na, 1.3185 (505),  $N_E = 1.3083$  Li, 1.3105 Na, 1.3201 (505),  $N_E - N_O = 0.0014$  Na. For  $N_O$ ,  $N_F - N_C = 0.0062$ . At  $65^\circ C.$ ,  $N_O = 1.3111$ ,  $N_E = 1.3125$ ,  $N_E - N_O = 0.0014$  Na (calc.).<sup>7</sup>

Water has  $N = 1.3308$  Li, 1.3330 Na; 1.3345 (535).

INVER. Under (varying) high pressures six other crystal phases of  $H_2O$  are known; one is isometric ( $a$  6.36 stable at  $100^\circ C.$ ), one tetragonal, and a third orthorhombic; optic data are lacking.

OCCUR. Ice is found in pores, fractures, and cavities in surface rocks in winter in cold climates; also found rarely at some depth below the surface. On lakes and shallow bays it forms crusts or layers composed of large acicular, irregularly arranged aggregates, or prisms arranged

<sup>3</sup> H. Schneiderhöhn and P. Ramdohr: *Lehrb. Erzmikr.*, II, 550 (1931).

<sup>4</sup> J. Orzel: *Bull. Soc. Fr. Min.*, LIII, 313 (1930).

<sup>5</sup> J. D. Bernal and R. H. Fowler: *Jour. Chem. Phys.*, I, 515 (1933).

<sup>6</sup> E. Blackwelder: *Am. Jour. Sci.*, CCXXXVIII, 61 (1939).

<sup>7</sup> A. Ehrlinghaus: *N. Jahrb. Min.*, Bl. Bd. XLI, 342 (1917).

with their vertical axes all normal to the surface of the lake. In cold regions ice may form large masses (glaciers) whose texture is like that of granular limestone. Ice in skeletal hexagonal platy crystals (of great variety) is *snow*. Ice in dendritic, stellate, or similar form is *frost*. Ice in crudely spherical aggregates (or, rarely, quartzoids) is *hail*.

Water is far more abundant than ice on and near the surface of the earth, forming springs, rivers, lakes, and oceans.

## 2. Simple oxides with type formula AX

**Periclase** (MgO) is isometric hexoctahedral. Space group<sup>8</sup>  $Fm\bar{3}m$ ;  $a$  4.203 Å. U.C. 4. Often octahedral, or cubic; usually granular. Perfect cubic and poor 111 cleavages. H. = 5.5–6. G. = 3.56–3.65. Fuses at 2800° C. Soluble in dilute HCl

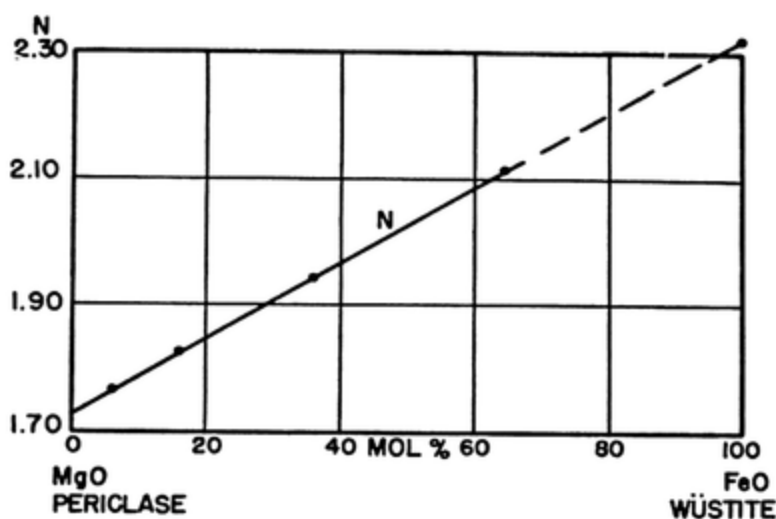


FIG. 36. Refractive index of the periclase-wüstite series.

or  $\text{HNO}_3$ . Isotropic with  $N = 1.736$  Na (and  $N_F - N_C = 0.010$ , for pure MgO) to 1.78 (with about 10% (Fe,Mn,Zn)O).<sup>9</sup> See Fig. 36. Colorless to yellowish or green. Alters readily to hydromagnesite, serpentine, or brucite. Found in limestone near igneous activity, etc., as at Vesuvius; also in contact zones, as at Nordmark, Sweden; Crestmore, California; etc.

**Wüstite** (FeO) is isometric with NaCl structure.  $a$ <sup>10</sup> 4.29 Å. It forms a complete series of artificial mix-crystals with MgO (see Fig. 36) and probably also with MnO (whose  $N = 2.16$ ).<sup>11</sup> Isotropic with  $N = 2.32$ .<sup>12</sup>  $N = 2.00$ .<sup>11</sup> Not certainly known in nature.

<sup>8</sup> R. W. G. Wyckoff: *Am. Jour. Sci.*, CCX, 107 (1925).

<sup>9</sup> See M. Haase: *Zeit. Krist.*, LXV, 509 (1927). Artificial crystals form a complete series from MgO to FeO with  $N$  varying from 1.736 to 2.32; see N. L. Bowen and J. F. Schairer: *Am. Jour. Sci.*, CCXXIX, 194 (1935).

<sup>10</sup> E. R. Jette and F. Foote: *J. Chem. Phys.*, I, 29 (1933).

<sup>11</sup> R. Graham and Hay: *Min. Abst.*, VI, 355 (1936).

<sup>12</sup> N. L. Bowen and J. F. Schairer: *Am. Jour. Sci.*, CCXXIX, 151 (1935).

**Bunsenite** (NiO) is isometric hexoctahedral. Space group <sup>13</sup>  $Fm\bar{3}m$ ;  $a$  4.171 Å.  $H.$  = 5.5.  $G.$  = 6.7–6.9.  $F.$  = 7. Slowly soluble in acid. Isotropic with  $N$  = 2.37 Li, 2.23 Na.  $N_F - N_C$  = 0.21 ±. Green or brownish black. Streak brownish black. Found in the oxide zone at Johanngeorgenstadt, Saxony.

**Manganosite** (MnO) is isometric hexoctahedral. Space group <sup>14</sup>  $Fm\bar{3}m$ ;  $a$  4.436 Å. Cubic cleavage.  $H.$  = 5.6.  $G.$  = 5.0–5.4.  $F.$  = 7. Slowly soluble in acid. Isotropic with  $N$  = 2.16 Li, 2.19 (green),  $N_F - N_C$  = 0.045 ±. Color emerald green, becoming black on exposure. Streak brown. Found at Långban and Nordmark, Sweden; and Franklin, New Jersey.

**Cadmium oxide** (CdO) is isometric hexoctahedral. Space group <sup>13</sup>  $Fm\bar{3}m$ ;  $a$  4.689 Å.  $H.$  = 3.  $G.$  = 8.1–8.2.  $F.$  = 7. Isotropic with  $N$  = 2.49 Li. Color black; red to brown in section. Found at Genarutta, Sardinia.

**Lime** (CaO) is isometric hexoctahedral <sup>15</sup> with cubic cleavage.  $a$  4.797 Å.  $H.$  = 3.5.  $G.$  = 3.3. Isotropic with  $N$  = 1.838. Colorless. Found at Vesuvius.

**Lithargite** (PbO) is tetragonal (ditetragonal-dipyramidal?) with  $c/a$  = 1.258. Space group <sup>16</sup> probably  $P4/nmm$ ;  $a$  3.986,  $c$  5.011 Å. U.C. 2. Crystals basal tablets with perfect 110 cleavage.  $H.$  = 2.  $G.$  = 9.13.  $F.$  = 1.5. Soluble in  $HNO_3$ . Uniaxial negative with  $N_O$  = 2.665 Li,  $N_E$  = 2.535,  $N_O - N_E$  = 0.130. Color yellowish red. Inverts at about 530°C. to  $\beta$ -PbO or *massicotite*. Found at Cucamonga Peak and Fort Tejon, California; also near Hailey, Idaho. Commercial litharge is usually a mixture of lithargite and *massicotite*.

**Zinkite** (ZnO) is dihexagonal pyramidal with  $c/a$  = 1.587; space group <sup>17</sup>  $C6mc$ ;  $a$  3.242,  $c$  5.176 Å. U.C. 2. Crystals rare, hemimorphic. Usually foliated massive or granular. Prismatic cleavage and basal parting.  $H.$  = 4.  $G.$  = (5.4–)5.7.  $F.$  = 7. Soluble in acids. Uniaxial positive with <sup>18</sup>  $N_O$  = 1.990 Li, 2.013 Na, 2.039 (530),  $N_E$  = 2.005 Li, 2.029 Na, 2.056 (530),  $N_E - N_O$  = 0.016 Na. For  $N_O$ ,  $N_F - N_C$  = 0.07 ±. Color deep red; rarely orange yellow. Streak orange yellow. In section deep red, not pleochroic. Polished surface light rose brown; reflection percentages: <sup>3</sup> red 8, orange 10, green 11. Alters to smithsonite. Found at Franklin, New Jersey.

**Bromellite** (BeO) is dihexagonal pyramidal with  $c/a$  = 1.629; space group <sup>19</sup>  $C6mc$ ;  $a$  2.68,  $c$  4.36 Å. U.C. 2. Crystals prismatic hemimorphic with distinct 10 $\bar{1}$ 0 cleavage.  $H.$  = 9.  $G.$  = 3.02.  $F.$  = 7. Insoluble. Uniaxial positive with  $N_O$  = 1.719,  $N_E$  = 1.733,  $N_E - N_O$  = 0.014. Colorless. Found at Långban, Sweden.

**Massicotite** (PbO) is orthorhombic with  $a:b:c$  = 0.932:1:0.807. Space group <sup>20</sup> probably  $Pbc$ ;  $a$  4.743,  $b$  5.476,  $c$  5.876 Å (art. cryst.). U.C. 4. Crystals {100} tablets with perfect 100 cleavage. Massive.  $H.$  = 2.  $G.$  = 9.3–9.56.  $F.$  = 1.5. Soluble in  $HNO_3$ . Axis Y (or X?) normal to 100. 2V = very large, +, except in blue, with strong dispersion.  $N_X$  = 2.51 Li;  $N_Y$  = 2.61,  $N_Z$  = 2.71,  $N_Z - N_X$  = 0.20. Color yellow with lighter streak; pleochroic with X (or Y?) = light sulfur

<sup>13</sup> W. L. Bragg: *Atomic Struct. Minerals* (1937).

<sup>14</sup> V. M. Goldschmidt: *Struktber.*, I, 122 (1931).

<sup>15</sup> R. W. G. Wyckoff: *Struct. Crystals* (1931).

<sup>16</sup> J. A. Darbyshire: *J. Chem. Soc. London*, 1932, p. 211.

<sup>17</sup> W. L. Bragg: *Atomic Struct. Minerals*, 1937, and T. F. W. Barth: *Norsk Geol. Tidsk.*, IX, 317 (1927).

<sup>18</sup> H. Berman: *Am. Mineral.*, XII, 168 (1927).

<sup>19</sup> G. Aminoff: *Z. Krist.*, LXII, 113 (1925).

<sup>20</sup> J. A. Darbyshire: *J. Chem. Soc. London*, 1932, p. 211; A. Byström: *Min. Abst.*, IX, 98, and 228 (1945); *abc* changed to *bac* to make  $b > a$ .



yellow, Z = deep yellow. Found in the oxide zone of some lead deposits, as at Freiberg, Saxony; Laurium, Greece; Leadville, Colorado; etc. Crystals commonly bordered by lithargite, probably the more stable phase.

**Montroydite** (HgO) is orthorhombic dipyramidal with  $a:b:c = 0.638:1:0.599$ . Space group <sup>21</sup>  $Pmmn$ ;  $a$  3.296,  $b$  3.513,  $c$  5.504 Å. U.C. 2. Crystals prismatic with 010 cleavage; also equant. Sectile and flexible. H. = 2. G. = 11.2 (Fron del).<sup>22</sup> Volatile. Soluble in HCl. The optic plane is 010 and  $Z = c$ . (+)2V = large,  $N_X = 2.37$ ,  $N_Y = 2.50$ ,  $N_Z = 2.65$ ,  $N_Z - N_X = 0.28$ . Color and streak orange red. Yellow in section and not pleochroic. Found at Terlingua, Texas, and Redwood, California.

**Tenorite** (CuO) is monoclinic prismatic with  $a:b:c = 1.498:1:1.365$ ,  $\beta = 99^\circ 29'$ . Space group <sup>23</sup>  $C2/c$ ;  $a$  4.65,  $b$  3.41,  $c$  5.11 Å. U.C. 4. Crystals lath shaped, often twinned.  $\bar{1}\bar{1}1$  and 001 cleavages. H. = 3.5. G. = 6.4. F. = 3. Soluble in HCl. The acute bisectrix (X?) is nearly normal to plates in which Z is parallel to the elongation.  $Y = b$ . 2V = large,  $r < v$ .  $N_Y = 2.63$  red, 3.18 blue,  $N_Z - N_X =$  strong. For  $N_Y$ ,  $N_F - N_C = 0.55$  ca. Color and streak black to iron gray, thin sections brown with Y = light brown, Z = very dark brown. Found in oxide zone of copper deposits, as at Siegen, Westphalia; Rio Tinto, Spain; Bisbee, Arizona; Vesuvius, Italy.

### 3. Simple oxides with type formula $A_2X_3$

**Sillenite** (Bi<sub>2</sub>O<sub>3</sub>) is isometric hextetrahedral; <sup>22</sup>  $a$  10.08 Å. U.C. 12. Soft. G. = 8.8. Isotropic with  $N > 2.42$ . Color green to yellow. Found at Durango, Mexico.

**Arsenolite** (As<sub>2</sub>O<sub>3</sub>) is isometric hexoctahedral; space group <sup>24</sup>  $Fd3m$ ;  $a$  11.046 Å. U.C. 16. Crystals octahedral. H. = 1.5. G. = (3.7–)3.8. F. = 1; volatile. Slightly soluble in H<sub>2</sub>O. Isotropic with  $N = 1.755$  Na; but may be anisotropic and biaxial. Color is white or tinted. An oxidation product of arsenical ores; also a smelter fume product; formed about burning coal mines.

**Senarmontite** (Sb<sub>2</sub>O<sub>3</sub>) is pseudoisometric (triclinic); space group above 460° C. is  $Fd3m$ ;  $a$  11.14 Å. U.C. 16. Crystals octahedral, with octahedral cleavage in traces. H. = 2–2.5. G. = (5.2–)5.5. F. = 1.5; volatile. Soluble in HCl. Isotropic with  $N = 2.087$  Na.  $N_F - N_C = 0.04$  ca. Often distinctly anisotropic (with 2V = large and  $N_Z - N_X = 0.0015$  ca.) in twinned areas as in boracite; becomes isotropic above 460° C. Colorless. An oxidation product of stibnite in ore deposits.

**Braunite** [(Mn,Si)<sub>2</sub>O<sub>3</sub>] is ditetragonal dipyramidal with  $c/a = 1.407$ ; space group <sup>25</sup>  $I4/acd$ ;  $a$  13.44,  $c$  18.93 Å. U.C. 64. Mn:Si = 7:1 nearly. May contain Fe''' at least to Mn:Fe''' = 5:1. Crystals pyramidal with perfect 112 cleavage. H. = 6–6.5. G. = 4.8. F. = 7. Soluble in HCl. Opaque. Color and streak dark brownish black to steel gray. Luster submetallic. In polished section grayish white and anisotropic. Reflection percentages:<sup>3</sup> red 16, orange 16.5, green 18.5. An ore of manganese, commonly found with other manganese minerals, as at Telmark, Norway, and Cartersville, Georgia.

<sup>21</sup> W. H. Zachariasen: *Zeit. phys. Chem.*, CXXVIII, 421 (1927).

<sup>22</sup> C. Palache, H. Berman, and C. Frondel: *Dana's Syst. Mineral.*, 7th Ed. (1944).

<sup>23</sup> G. Tunell, E. Posnjak, and C. J. Ksanda: *Zeit. Kryst.*, XC, 120 (1935).

<sup>24</sup> R. M. Bozorth: *J. Am. Chem. Soc.*, XLV, 1621 (1923); F. Lihl: *Zeit. Krist.*, LXXXI, 142 (1931).

<sup>25</sup> G. Aminoff: *Handl. Sk. Stockholm*, IX, 14 (1931); G. Switzer: *Am. Mineral.*, XXIII, 649 (1938).



**Russellite**  $[(Bi_2,W)O_3?]$  is tetragonal (scalenohedral?) with  $c/a = 2.084$ . Space group <sup>26</sup>  $I\bar{4}2d$  or  $I4/amd$ ;  $a$  5.42,  $c$  11.3 Å. U.C. 4. It is an isomorphous mixture of  $Bi_2O_3$  and  $WO_3$  ranging from 1:1 to 1:2. H. = 3.5. G. = 7.35. Color pale yellow to greenish. Uniaxial positive with  $N = 2.2 \pm$ . An alteration product found with wolframite, topaz, etc., at the Castle-on-Dinas mine in Cornwall.

**CORUNDUM** HEXAGONAL SCALENOHEDRAL  $c/a = 1.364$   $Al_2O_3$

STRUC.<sup>27</sup> Space group  $R3c$ ;  $a$  4.751,  $c$  12.97 Å. Rhombohedral U.C. 2.

PHYS. CHAR. Crystals usually hexagonal pyramids with the base. Angles often rounded. Twinning on  $10\bar{1}1$  may be simple or multiple. No cleavage; basal parting sometimes perfect;  $10\bar{1}1$  parting less common. H. = 9. G. = 3.95–4.10. Fuses at 2035° C. Insoluble in acids.

OPT. PROP. Uniaxial negative, but often in part biaxial with  $2E = 10\text{--}12^\circ$ —in one case  $58^\circ$ .<sup>28</sup> Birefringence weak; refringence high, increasing slightly in red corundum with depth of color.

Colorless or Pale Blue				F - C	Dark Red (Ruby)			
N <sub>O</sub> = 1.7653	C	1.7686	D	1.776	F	0.0107	1.7717	D
N <sub>E</sub> = 1.7573	C	1.7604	D	1.7677	F	0.0104	1.7632	
N <sub>O</sub> - N <sub>E</sub> = 0.0080	C	0.0082	D	0.0083	F		0.0085	

Colorless, white or gray (*ordinary corundum*), blue (*sapphire*), red (*ruby*), yellow (*oriental topaz*), green (*oriental emerald*). The term sapphire is often used to designate any colored corundum of gem quality except red. Darkly colored crystals are pleochroic with absorption  $O > E$  and  $O =$  indigo blue, blue, deep purple,  $E =$  light blue, emerald to yellow-green, light yellow. Asterism is not rare, due to oriented acicular inclusions.

ALTER. Alteration products include muscovite, spinel, kyanite, sillimanite, etc.

OCCUR. Corundum is usually found in crystalline metamorphic rocks such as marble, mica or chlorite schist, gneiss, etc. Also found in eruptive rocks and in rocks metamorphosed locally by eruptives.

DIAG. It is distinguished by very high relief and weak birefringence; also by its form, hardness, specific gravity, and insolubility.

**Taosite**  $[(Al,Ti)_2O_3?]$  is uniaxial <sup>29</sup> negative with  $N = 1.78$  ca.,  $N_O - N_E = 0.035$ . Color red with  $O =$  reddish brown,  $E =$  clear yellow. An alteration product of diaspore associated with spinel; the plates of taosite are parallel to octahedral faces of spinel. Found at Samos, Greece.

<sup>26</sup> M. H. Hey and F. A. Bannister: *Mineral. Mag.*, XXV, 41 (1938).

<sup>27</sup> L. Pauling and S. B. Hendricks: *J. Am. Chem. Soc.*, XLVII, 781 (1925).  $c/2:a = 1.365:1$ .

<sup>28</sup> E. Bertrand: *Bull. Soc. Fr. Min.*, I, 94 (1875).

<sup>29</sup> J. de Lapparent: *Compt. Rend. Acad. Sci. Paris*, CCI, 154 (1935).

**HEMATITE**      **HEXAGONAL SCALENOHEDRAL**       $c/a = 1.365$        $\text{Fe}_2\text{O}_3$

STRUC.<sup>27</sup> Space group  $R3c$ ;  $a$  5.029,  $c$  13.73 Å. Rhombohedral U.C. 2.

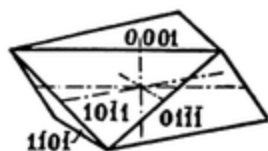


FIG. 37. A crystal habit of hematite.

PHYS. CHAR. Crystals of varied habit; rhombohedral faces usually prominent with or without the base. See Fig. 37. Sometimes platy, fibrous, or massive. No cleavage, but may have basal or rhombohedral parting, due to polysynthetic twinning.  $H. = 5-6$ .  $G. = 5.2$ .  $F. = 7$ , but becomes magnetic in reducing flame. Soluble in  $\text{HCl}$ .

OPT. PROP. Uniaxial negative. Refrindex very high and birefringence very strong.

$N_O = 2.988$ (686)	$3.042$ Li	$3.22$ Na	$3.15$ Na <sup>30</sup>	$N_F - N_C = 0.5$ ca.
$N_E = 2.759$ (686)	$2.797$ Li	$2.94$ Na	$2.87$ Na	
$N_O - N_E = 0.229$ (686)	$0.245$ Li	$0.28$ Na	$0.28$ Na	
Again <sup>31</sup> $N_O = 2.769$ (852), $N_E = 2.690$ , $N_O - N_E = 0.079$ .				

Color of crystals steel gray to iron black with good to brilliant luster (*specularite*). Earthy varieties red. Streak red. Opaque except in very thin scales which are blood red and slightly pleochroic, as follows:  $O =$  brownish red,  $E =$  yellowish red. Hematite crystals produce marked rotation of the plane of polarization of reflected light. Reflection percentages:<sup>3</sup> red 21, orange 25, green 26. Again:<sup>4</sup> white 0.29 and 0.267.

INVER. Hematite shows a sharp inversion point at  $678^\circ \text{C}$ . Another inversion is reported at  $-40^\circ \text{C}$ .

ALTER. Hematite is a common alteration product, but it may itself alter to magnetite, siderite, limonite, pyrite, etc.

OCCUR. Forms large deposits in some sedimentary rocks. One of the most widely distributed of minerals. Found as a product of contact metamorphism and in various crystalline schists. Common in many veins, especially in the oxide zone. Product of fumaroles about volcanoes. Rather common as microscopic inclusions and alteration products in many minerals and rocks, coloring them red.

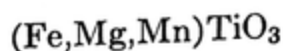
DIAG. Hematite is easily distinguished from magnetite and ilmenite by the deep red color of thin scales or of powder; but hematite in crystals or in very compact masses in thin section is opaque and black or metallic in reflected light. Cinnabar has the color of massive hematite, but it has perfect hexagonal prismatic cleavage, is positive, and is of very re-

<sup>30</sup> M. Berek: *Mit. Leitz Werke*, 63, 1 (1941).

<sup>31</sup> R. Bailly: *Am. Mineral.*, XXXIII, 519 (1948).

stricted occurrence. Moreover it has much higher specific gravity (8-8.2) than hematite.

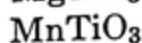
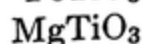
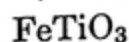
# ILMENITE RHOMBOHEDRAL



**Crichtonite.**  $c/a = 1.380$ .

**Geikielite.**  $c/a = 1.386$ .

**Pyrophanite.**  $c/a = 1.398$ .



**COMP.** Ilmenite varies greatly in composition, from  $\text{FeTiO}_3$  to  $\text{MgTiO}_3$  and to  $\text{MnTiO}_3$ . Senaitite  $[(\text{Fe}, \text{Mn}, \text{Pb})\text{TiO}_3]$  is supposed to belong to the same system. Only a little  $\text{Fe}_2\text{O}_3$  seems to be possible in ilmenite.

**STRUC.** Space group  $R\bar{3}$ . Rhombohedral U.C. 2. Cell dimensions.<sup>32</sup>

	$a_{\text{rh}}$	$\alpha$	$a$	$c$	$a:c/2$
Crichtonite	5.52	$54^\circ 50'$	5.083	14.04	1:1.380
Geikielite	5.54	$54^\circ 39'$	5.086	14.093	1:1.386
Pyrophanite	5.62	$54^\circ 16'$	5.126	14.33	1:1.398

**PHYS. CHAR.** Crystals rhombohedral with base, etc. Often lamellar or massive. Crichtonite has no cleavage; geikielite has good  $10\bar{1}1$  cleavage; pyrophanite has perfect  $02\bar{2}1$  and good  $10\bar{1}2$  cleavages.  $H. = 5-6$ .

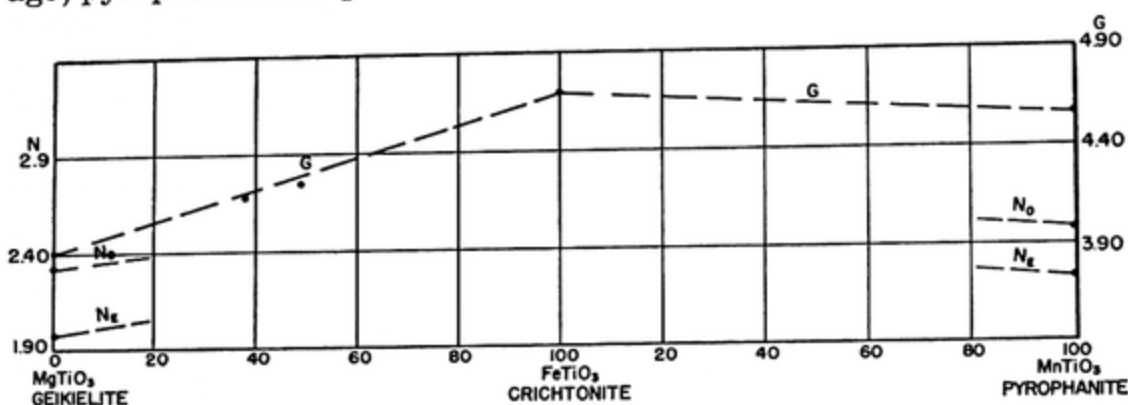


FIG. 38. Properties of the ilmenite double series.

$G.$  for crichtonite (4.6-4.72), for geikielite (3.8-4.05), for pyrophanite 4.54, for senaitite 4.8-5.3. See Fig. 38.  $F. = 7$ . Slowly soluble in  $\text{HCl}$ .

**OPT. PROP.** Crichtonite is opaque; rarely slightly translucent and dark brown with extremely high refringence and very strong birefringence. Color in mass black; streak black. Luster metallic. In reflected light violet-black. Reflection percentage: red, orange, and green, 18. Crichtonite is optically negative.<sup>33</sup>

<sup>32</sup> T. F. W. Barth and E. Posnjak: *Zeit. Krist.*, LXXXVIII, 265, 275 (1934).

<sup>33</sup> L. Capdecombe: *Bull. Soc. Fr. Min.*, LXIV, 171 (1941).

Geikielite is translucent in thin section and deep reddish purple; uniaxial negative with  $N_O = 2.31$ ,  $N_E = 1.96$ ,  $N_O - N_E = 0.36$ . Weak absorption with  $O < E$ . Color in mass black with metallic luster. Streak purplish brown.

Pyrophanite is yellowish red in thin section; uniaxial negative with  $N_O = 2.441$  Li,  $2.481$  Na,  $N_E = 2.210$  Na,  $N_O - N_E = 0.271$  Na. Not pleochroic. Color in mass deep blood red. Streak ocher yellow, slightly greenish.

Senaite is green to greenish brown in thin section; uniaxial negative with  $N_O = 2.50$  Li. Color in mass black; nearly opaque and not pleochroic.  $H. = 6$ .  $G. = 5.3$ .

All these optical properties vary with variations in composition. Some of these variations are shown in Fig. 38.

**ALTER.** Ilmenite often alters to *leucoxene*, an opaque whitish aggregate<sup>34</sup> of rutile or, rarely, anatase. In phyllites, ilmenite alters to siderite and rutile; rarely to anatase.

**OCCUR.** Ilmenite (near crichtonite) is a common, but only sparse, constituent of igneous rocks; not rare in metamorphic rocks; found in veins and alluvial sands. Geikielite is found in gem placers in Ceylon. Pyrophanite occurs in ore deposits in Sweden. Senaite is found in diamond-bearing sands of Brazil.

**DIAG.** Ilmenite (near crichtonite) is only slightly magnetic; in thin section it is distinguishable from magnetite with much difficulty—the leucoxene alteration is evidence of titanium. Geikielite and pyrophanite are characterized by color and other optic properties. A rapid and convenient microchemical test for titanium can be made by dissolving the mineral (a minute amount is sufficient) in HCl, and adding a drop of the solution to an  $H_2SO_4$  solution of morphine, producing a crimson color, or of phenol, producing a brick red color, or of papaverine, producing a violet color.

**Valentinite** ( $Sb_2O_3$ ) is orthorhombic dipyramidal with  $a:b:c = 0.394:1:0.434$ . Space group<sup>35</sup> *Pccn*;  $a$  4.92,  $b$  12.46,  $c$  5.42 Å. U.C. 4. Crystals prismatic or tabular parallel to 010, or elongated along  $a$ , with perfect 110 cleavages.  $H. = 2.5-3$ .  $G. = 5.76$ . Easily fusible and somewhat volatile. Soluble in HCl. The acute bisectrix  $X$  is normal to 100; the optic angle is very small and varies through  $0^\circ$  so that the optic plane is 001 in red and yellow light and 010 in blue and green light.<sup>36</sup> Again, the optic plane is 001 for all colors.<sup>37</sup>  $(- )2V = 10^\circ$  red,  $25^\circ$  blue.  $N_X = 2.18$  Na,  $N_Y = 2.352$ ,  $N_Z = 2.358$ ,  $N_Z - N_X = 0.178$ . When heated to  $75^\circ$  the optic angle for red decreases and for blue increases. Colorless (white in mass—rarely tinted). An oxidation product of antimony ores, as at Příbram, Bohemia; Siena, Italy; and South Ham, Quebec.

<sup>34</sup> S. A. Tyler and R. W. Marsden: *J. Sed. Petrol.*, VIII, 55 (1938).

<sup>35</sup> M. J. Buerger and S. B. Hendricks: *J. Chem. Phys.*, V, 600 (1937).

<sup>36</sup> L. J. Spencer: *Mineral. Mag.*, XIV, 328 (1907).

<sup>37</sup> A. Davinato: *Min. Abst.*, VII, 160 (1938).

**Claudetite** ( $As_2O_3$ ) is monoclinic prismatic with  $a:b:c = 0.409:1:0.349$ ,  $\beta = 94^\circ 20'$ . Space group  $^{38} P2_1/n$ ;  $a$  5.25,  $b$  12.87,  $c$  4.54 Å. U.C. 4. Crystals prismatic or {010} tablets. Penetration twinning on 100 common. Perfect 010 and good 110 cleavages.  $H. = 2.5$ .  $G. = 4.15$ . Volatile. The optic plane is 010;  $Z \wedge c = -6^\circ$ .  $(+ )2V = 58^\circ$ ,  $r > v$  strong.  $N_X = 1.87$ ,  $N_Y = 1.92$ ,  $N_Z = 2.01$ ,  $N_Z - N_X = 0.14$ . Colorless to white. An oxidation product of arsenic ores, notably arsenopyrite; also formed about burning coal mines and in smelter fumes.

**Bismite** ( $Bi_2O_3$ ) is monoclinic prismatic with  $a:b:c = 0.716:1:0.919$ ,  $\beta = 112^\circ 56'$ . Space group  $P2_1/c$ ;  $^{39} a$  5.83,  $b$  8.14,  $c$  7.48 Å. U.C. 4. Massive.  $H. = 4.5$ .  $G. = 9.2$ ;  $^{40} 8.64$ .<sup>41</sup> Biaxial with strong dispersion and indices above 2.42. Color and streak grayish green (natural) or yellow (artificial). An oxidation product of bismuth ores.

#### 4. Simple oxides with type formula $AX_2$

**Thorianite** ( $ThO_2$ ) is isometric hexoctahedral;<sup>42</sup>  $a$  5.61 Å. Artificial crystals form a complete series from  $ThO_2$  to  $UO_2$ ; in natural crystals  $UO_2$  known to  $U:Th = 1:1$ . Crystals cubic.  $H. = 6.5$ .  $G. = (9.3- ) 9.7$ .  $F. = 7$ . Soluble in  $HNO_3$ . Strongly radioactive. Isotropic and nearly opaque with  $N = 2.20$  ca. Color black. Streak gray. Reddish brown in section. Found in gem washings and pegmatite in Ceylon.

**Uraninite** ( $UO_2$ ) is isometric hexoctahedral.<sup>42</sup>  $a$  5.47 Å. U.C. 4. Natural material always partly oxidized, grading toward  $U_3O_8$ ; Th usually present—up to 14 per cent. Pb always present, due to radioactive decay of U and Th. He, A, N commonly present. Also rare earths and many other elements in small amounts. Crystals octahedral or cubic; usually massive.  $H. = 5-6$ .  $G. = (8- ) 10.9$ . The specific gravity decreases with oxidation. Often altered to an amorphous or "metamict" state (*pitchblende*) with about 2-5%  $H_2O$  and  $G. =$  about 6 to 8.  $F. = 7$ . Soluble in  $HNO_3$ . Not magnetic. Usually opaque; otherwise greenish, yellowish, or deep brown. Streak brownish black, gray, or olive green. Luster submetallic to greasy or pitchlike; also dull. In polished section light gray with a brownish tint. Reflection percentages:<sup>3</sup> red 12.5, orange 12.5, green 15; with Th: red 14, orange 14, green 15.5. Alters easily. Found in pegmatite and metalliferous veins, as at Joachimstal, Bohemia, in the Belgian Congo, and near Great Bear Lake in northern Canada.

**Stibiconite**<sup>43</sup> ( $Sb_2O_3 \cdot Sb_2O_5 \cdot nH_2O?$ ) is isometric hexoctahedral(?).  $H. = 4-5$ .  $G. = 5.1-5.6$ .  $F. = 7$ . Insoluble. Isotropic with  $N = 1.6-2.0$ . Often mixed with fibrous birefringent material (cervantite?) with  $N = 1.67-2.05$  and  $N_Z - N_X =$  weak to strong. The cause of these variations is unknown—are several minerals present, or one mineral varying much in composition? Stibiconite is pale yellow to nearly white, or reddish. Found in ore deposits, as at Zamora, Spain; South Ham, Quebec; Antimony, Utah; etc.

<sup>38</sup> M. J. Buerger: *Dana's Syst. Mineral*; 7th Ed., 546 (1944).

<sup>39</sup> L. G. Sillen: *Ark. Kemi.*, XII, 1938; *Zeit. Krist.*, CIII, 274 (1941).

<sup>40</sup> A. Carnot: *Comp. Rend.*, LXXIX, 478 (1874).

<sup>41</sup> C. Frondel: *Am. Mineral.*, XXVIII, 521 (1943).

<sup>42</sup> V. M. Goldschmidt and L. Thomassen: *Vid. Selskr. Oslo, Math.-Nat. Kl.*, 1923, No. 2.

<sup>43</sup> The artificial compound  $Sb_3O:OH$  crystallizes in the space group  $Fd3m$  with  $a$  10.28 Å. Dihlstrom and Westgren: *Zeit. anorg. Chem.*, CCXXXV, 153 (1937); is this artificial stibiconite?

**RUTILE** DITETRAGONAL DIPYRAMIDAL  $c/a = 0.644$   $\text{TiO}_2$

**COMP.** May contain up to at least 36%  $\text{Ta}_2\text{O}_5$ , 32%  $\text{Nb}_2\text{O}_5$ , and 16%  $\text{FeO}$ , probably as  $\text{Fe}(\text{Ta,Cb})_2\text{O}_6$ —then called *strüverite*; also less  $\text{Fe}_2\text{O}_3$ ,  $\text{MnO}$ ,  $\text{SnO}_2$ , etc.

**STRUC.**<sup>44</sup> Space group  $P4/mnm$ ;  $a$  4.58,  $c$  2.95. U.C. 2.

**PHYS. CHAR.** Crystals nearly always elongated parallel to  $c$ , sometimes finely fibrous, and vertically striated. Twinning on 011 frequent

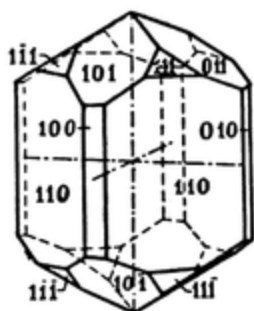


FIG. 39. A crystal habit of rutile.

in macroscopic crystals; this type is known as geniculated twinning when composed of two parts; when it has several parts, they may be arranged in a cycle of six or eight (called cyclic twinning), or they may form lamellae visible microscopically in basal sections. Twinning also on 031 rare in large crystals, but common in microscopic ones. Twinning on 092 as a glide plane producing parting. The reticulated groups in *sagenite* are often due to a combination of twinning types. Good prismatic cleavage.  $H. = 6-6.5$ .  $G.$

$= 4.2$ , increasing to 4.6 with about 30 mol. per cent of  $\text{FeNb}_2\text{O}_6$ , and to 5.3 with about 25 mol. per cent of  $\text{FeTa}_2\text{O}_6$ , and to 5.56 in *strüverite*.  $F. = 7$ . Insoluble.

**OPT. PROP.** Uniaxial positive with the highest refringence found in any rock-forming mineral and extreme birefringence. Indices<sup>45</sup> measured at  $25^\circ \text{C}$ . (except last two columns) on a crystal having  $G = 4.219$ :

$\lambda = 546$	589	623	691	$F - C$ (calc.)	589 at $150^\circ \text{C}$ .	589 at $450^\circ \text{C}$
$N_E = 2.9467$	2.8893	2.8712	2.8294	0.1665	2.8888	2.8679
$N_O = 2.6505$	2.6124	2.5890	2.5555	0.1316	2.6062	2.5953
$N_E - N_O = 0.2962$	0.2869	0.2822	0.2739	0.0349	0.2826	0.2726

Rutile with 98.96  $\text{TiO}_2$ , 0.78  $\text{FeO}$ , 0.38  $\text{H}_2\text{O}$ , 0.13  $\text{V}_2\text{O}_3$ , and 0.03  $\text{Cr}_2\text{O}_3$  has<sup>46</sup>

$N_E = 2.8352$ Li	2.8948 Na	2.9569 Tl	Average of measures on two crystals.
$N_O = 2.5609$ Li	2.6090 Na	2.6582 Tl	
$N_E - N_O = 0.2743$ Li	0.2858 Na	0.2987 Tl	

With much  $\text{Fe}(\text{Ta,Nb})_2\text{O}_6$ ,  $N_O$  may be as low as 2.50 (*strüverite*).

Color red, reddish brown, brownish black, yellow, bluish, violet, rarely green. Streak pale brown. In thin section pleochroism very weak to

<sup>44</sup> M. L. Huggins: *Phys. Rev.*, XXVII, 638 (1926).

<sup>45</sup> A. Schroeder: *Zeit. Krist.*, LXVII, 485 (1928).

<sup>46</sup> L. Baric: *N. Jahrb. Min.*, I, 472 (1936).



distinct with O = yellow to brownish, E = brown-yellow to yellow-green; in thicker sections O = brownish red, E = dark blood red to black. Fe<sup>+++</sup>, Ta, and Nb make the colors darker. In strüverite O = brown, E = green and nearly opaque.

Rutile sometimes shows biaxial (twinned) bands in basal sections; in these bands the optic plane is 110; the biaxial character may be due to twinning or to deformation.

In polished sections, color light gray and weakly pleochroic. Reflection percentages:<sup>3</sup> red 17.5, orange 18, green 20.5. Again<sup>47</sup> white  $R_E = 0.25$ ,  $R_O = 0.21$ .

ALTER. Rutile is comparatively a very stable mineral; nevertheless, it undergoes various changes in nature. One of the most common is the change to ilmenite; this can be observed in all its stages in various sections; the ilmenite forms about the borders and then along the cleavage planes of the rutile. Occasionally rutile may be changed into titanite—a process which is sometimes reversed.

INVER. Rutile is the stable form of  $TiO_2$  at high temperatures and perhaps the most stable at all temperatures.

OCCUR. Rutile occurs in nature as very small crystals sparsely, but very widely, distributed; larger crystals are rarely found, chiefly in pegmatites. Minute crystals are sometimes produced by alteration as when biotite or amphibole alters to chlorite. They are common in metamorphic rocks such as amphibolites, eclogites, gneisses, schists, etc., also common in some sedimentary rocks, as well as in some rocks produced by contact metamorphism. Finally rutile is found in many veins, commonly associated with quartz, calcite, topaz, pyrite, sphalerite, etc.

DIAG. Rutile is distinguished by its (usual) deep red color, very high relief and extreme birefringence; it is also characterized by brilliant luster, distinct prismatic cleavages, and high density.

**Pyrolusite** ( $MnO_2$ ) is ditetragonal dipyramidal with  $c/a = 0.665$ . Space group  $P4/mnm$ ;  $a$  4.38,  $c$  2.86 Å. U.C. 2. Crystals rare (*polianite*); usually massive or powdery. Perfect 110 cleavage. H. = 2–6. G. = (4.4)–5. Opaque. Optically positive.<sup>49</sup> Luster metallic. Color steel gray. Streak black. In polished section



FIG. 40. Rutile in thin section of a rock.

<sup>47</sup> J. Orcl: *Bull. Soc. Fr. Min.*, LIII, 301 (1930).

<sup>48</sup> A. Ferrari: *Atti Accad. Linc.*, III, 224 (1926).

<sup>49</sup> L. Capdecombe: *Bull. Soc. Fr. Min.*, LXVI, 79 (1943).



cream white and distinctly anisotropic. Reflection percentages: <sup>3</sup> red 27.5, orange 32.5, green 34. An important ore of manganese, as at Siegen, Westphalia; Platten, Bohemia; Kutais, Russia; Hillsborough, Canada; Batesville, Arkansas; etc.

**CASSITERITE** DITETRAGONAL DIPYRAMIDAL  $c/a = 0.672$   $\text{SnO}_2$

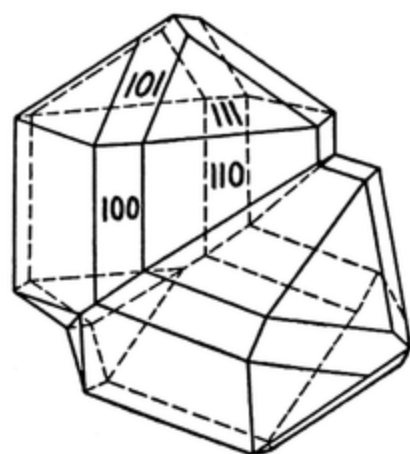


FIG. 41. A geniculated twin of cassiterite.

COMP. May contain  $\text{Fe}_2\text{O}_3$ ,  $\text{Ta}_2\text{O}_5$ ,  $\text{Cb}_2\text{O}_5$ ,  $\text{MnO}$ , and  $\text{WO}_3$  in small amounts (e.g., to total of about 20%—then G. increases).

STRUC.<sup>50</sup> Space group  $P4/mnm$ ;  $a$  4.72,  $c$  3.17 Å. U.C. 2.

PHYS. CHAR. Crystals short prismatic or pyramidal with poor prismatic cleavage. Parting on 011. Twinning as in rutile.  $H. = 6-7$ .  $G. = (6.1-7.0)$ . Cleavage reported on 001.

OPT. PROP. Uniaxial positive with extreme refringence and birefringence. Refringence decreases and birefringence increases with increase of wave length.

$\lambda =$	444	486	585	653	715	F - C	G - B <sup>51</sup>
$N_E =$	2.1397	2.1226	2.0972	2.0874	2.0818	0.0355	0.064
$N_O =$	2.0475	2.0282	2.0006	1.9899	1.9836	0.0387	0.071
$N_E - N_O =$	0.0922	0.0944	0.0966	0.0975	0.0982	-0.0032	-0.007

For  $\lambda = 578$ ,  $N_O = 2.0007$  at 16° C., 2.0316 at 533° C., and 2.0706 at 1014° C.

For  $\lambda = 578$ ,  $N_E = 2.0980$  at 16° C., 2.1275 at 533° C., and 2.1658 at 1014° C.

Cassiterite (from Siberian localities)<sup>52</sup> may show zonal structure and optic anomalies with  $2V$  up to 38°, ( $r < v$ ) and  $N_O$  varying from 1.989 to 2.013. Cassiterite<sup>53</sup> with 3.26  $\text{Ta}_2\text{O}_5$  has  $G. = 7.015$  and  $N_O = 2.002$ .

Color usually brown to black, but may be red, yellow, gray, or white; color may be irregularly distributed or in zones or bands. Luster adamantine. Streak white to brownish. In thin section colorless, yellowish, brown, or reddish. Rarely pleochroic with  $O =$  yellow to iron gray,  $E =$  yellow-brown to black; again  $O =$  colorless,  $E =$  pink;  $O =$  clear green,  $E =$  red,  $O =$  pale grayish green to greenish brown,  $E =$  reddish brown to deep red-brown.<sup>54</sup> Absorption  $O < E$ .

<sup>50</sup> W. P. Davey: *Phys. Rev.*, XXIII, 763 (1924).

<sup>51</sup> C. J. Payne: *Min. Abst.*, VII, 518 (1940).

<sup>52</sup> J. D. Gotman: *Min. Abst.*, VII, 463 (1940).

<sup>53</sup> G. Pehrman: *Acta Acad. Abo.*, XV, No. 2 (1945).

<sup>54</sup> W. R. Liebenberg: *Trans. Geol. Soc. S. Africa*, XLVIII, 1 (1945).

In polished section light gray and strongly anisotropic; reflection percentages:<sup>3</sup> red 8.5, orange 10, green 11. Again:<sup>47</sup> white  $R_0 = 0.11$ ,  $R_E = 0.124$ .

**INVER.** Hexagonal and orthorhombic forms of  $SnO_2$  have been made artificially, but the stability relations are unknown.

**OCCUR.** Usually produced by the action of mineralizers from acid granites in veins or pegmatites. Also found in sulfide veins; also in stream gravels. Localities include Marienbad, Saxony; Cornwall, England; Banka, East Indies; and Arandis, Southwest Africa.

**DIAG.** Distinguished from rutile by lighter color (usually) and by less extreme birefringence producing bright interference colors, instead of the indefinite grays of the higher orders, in very thin sections.

**Plattnerite** ( $PbO_2$ ) is ditetragonal dipyramidal with  $c/a = 0.683$ . Space group  $P4/mnm(?)$ ;  $a$  4.931,  $c$  3.367 Å. U.C. 2. Crystals prismatic; usually massive. No cleavage.  $H. = 5.5$ .  $G. = (8.5-9.45)$ .  $F. = 2$ . Soluble in HCl. Uniaxial negative with  $N_0 = 2.30 \pm 0.05$  Li. Also biaxial in twinned pseudotetragonal groups. Translucent to nearly opaque. Color iron black. Streak brown. In polished section gray-white and anisotropic; reflection percentages:<sup>3</sup> red 11, orange 13, green 16.5. Found in lead mines in Scotland and Idaho. Differs from other minerals of the rutile group by mode of occurrence and negative sign.

**ANATASE (Octahedrite)** DITETRAGONAL DIPYRAMIDAL  $c/a = 2.513$   $TiO_2$

**STRUC.** Space group  $I4/amd$ ;  $a$  3.73,  $c$  9.37 Å. U.C. 4.

**PHYS. CHAR.** Commonly pyramidal or tabular or prismatic. Distinct 001 and 011 cleavages.  $H. = 5.5-6$ .  $G. = 3.82-3.97$ .  $F. = 7$ . Insoluble.

**OPT. PROP.** Uniaxial negative with extreme refringence. Indices vary remarkably (why?), for example: on a yellow crystal:  $N_0 = 2.501$  Na;  $N_E = 1.431$ ; on a gray crystal  $N_0 = 2.556$ . Crystals from Binnental,<sup>57</sup> with  $G. = 3.904$ , give (at 25° C., except last two):

	671.6	589	491.6	F - C (calc.)	589 at 300° C.	589 at 750° C.
$N_0 = 2.5179$		2.5612	2.6584	0.1245	2.5545	2.5486
$N_E = 2.4518$		2.4880	2.5688	0.1233	2.4859	2.4858
$N_0 - N_E = 0.0661$		0.0732	0.0996	0.0012	0.0686	0.0628
$N_0 - N_E' = 0.053$ on the pyramidal cleavage. <sup>58</sup>						

Abnormal biaxial crystals, with small optic angle, not rare.

Color brown, yellow, blue, black. In section lighter shades of these colors, sometimes irregularly or zonally arranged. Pleochroism usually weak with  $0 < E$ ; sometimes  $O > E$ . For example  $O =$  yellow, blue, green,  $E =$  brown, deep blue, sky blue.

<sup>55</sup> L. Vegard: *Phil. Mag.*, XXXII, 65 (1916), and I, 1151 (1926).

<sup>56</sup> H. Buttgenbach: *Min. Abst.*, VII, 217 (1939).

<sup>57</sup> A. Schroeder: *Zeit. Krist.*, LXVII, 485 (1928).

<sup>58</sup> H. Buttgenbach: *Minéraux et Roches*, 508 (1916).

**INVER.** Artificially anatase is produced at low temperatures, brookite at intermediate, and rutile at high temperatures. But rutile may form at low temperature in nature. Anatase inverts to rutile<sup>59</sup> at 800°–900° C.

**OCCUR.** Anatase is found in veins in igneous rocks and schists; occasionally, an alteration product of sphene or ilmenite. Localities include Cavradi, Switzerland; Pisek, Bohemia; Kragerö, Norway; Sherbrooke, Nova Scotia.

**DIAG.** Anatase is easily distinguished from rutile and brookite by its uniaxial negative character. The usually pyramidal crystal form is also distinctive.

## BROOKITE

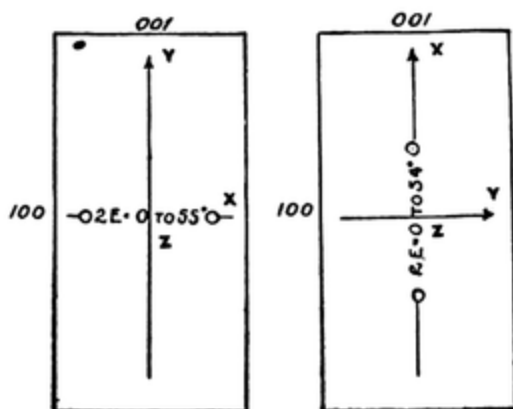
### ORTHORHOMBIC DIPYRAMIDAL

TiO<sub>2</sub>

$$a:b:c = 0.594:1:0.561$$

**STRUC.** Space group<sup>60</sup> *Pcab*; *a* 5.436, *b* 9.166, *c* 5.135 Å. U.C. 8.

**PHYS. CHAR.** Found only as crystals, of varied habit. Cleavage only in traces parallel to 120 and 001. *H.* = 5.5–6. *G.* = (3.87–)4.1. *F.* = 7. Insoluble even in HF.



FIGS. 42, 43. The optic orientation of brookite for red and blue light.

**OPT. PROP.** Biaxial positive with extreme refringence and birefringence; also extraordinary dispersion of optic axes—the positive acute bisectrix (*Z*) is normal to 010 in all cases, but the optic plane is 001 for red and yellow light with  $r < v$  and 100 for green and blue light with  $r > v$ ; the mineral is uniaxial for a certain yellowish green tint ( $\lambda$  = about 555  $\mu$  at 25° C.; varies from 546 to 562  $\mu$ ). Rarely, the optic plane is 001 for all colors.<sup>61</sup> For constant wave length, decreasing temperature decreases the optic angle in 001 (for example,<sup>62</sup> 2*E* for red decreases from 54° at 25° C. to 26° at

–190° C., being then uniaxial for yellow light) and increases the optic angle in 010. The mineral shows abnormal interference colors and no extinction.

	F – C						
	(calc.)						
$\lambda^{63} = 671.6$	589	579.1	555±	546.1	513.2	491.6	
(+)2 <i>E</i> = 58° 7'		25° 48'	0°		47° 5'	68° 16'	
<i>N<sub>X</sub></i> = 2.5405	2.5831	2.5895		2.6154	2.6472	2.6717	0.1341
<i>N<sub>Y</sub></i> = 2.5443	2.5843	2.5904		2.6159	2.6502	2.6770	0.1373
<i>N<sub>Z</sub></i> = 2.6519	2.7004	2.7091		2.7402		2.809	0.1623
<i>N<sub>Z</sub></i> – <i>N<sub>X</sub></i> = 0.1114	0.1173	0.1196		0.1248		0.1373	0.0282

For  $\lambda = 589$  at 300° C.: *N<sub>X</sub>* = 2.5880, *N<sub>Y</sub>* = 2.5897, *N<sub>Z</sub>* = 2.6762, and at 600° C. *N<sub>X</sub>* = 2.5924, *N<sub>Y</sub>* = 2.5981, *N<sub>Z</sub>* = 2.6610.

<sup>59</sup> A. V. Pamfilov and E. G. Ivancheva: *Min. Abst.*, VIII, 182 (1942).

<sup>60</sup> L. Pauling and J. H. Sturdivant: *Zeit. Krist.*, LXVIII, 239 (1928).

<sup>61</sup> R. H. Rastall: *Geol. Mag.*, LXXV, 433 (1938).

<sup>62</sup> U. Panichi: *Zeit. Kryst.*, XL, 86 (1905).

<sup>63</sup> A. Schroeder: *Zeit. Krist.*, LXVII, 485 (1928).

Color brown, yellowish, reddish, black. In thin section weakly pleochroic in yellow or brown tints; absorption either  $X < Y < Z$  or  $X < Z < Y$ . For example:

X = Orange	Cinnamon brown	?
Y = Orange	Clove brown	Nearly colorless
Z = Lemon yellow	Clove brown	Wine yellow or orange-red

**INVER.** Brookite changes to rutile at high temperature ( $700^\circ \pm C.$ ).

**OCCUR.** Found in veins of igneous and metamorphic rocks, and as a secondary product in various rocks; also in placers. Localities include Sondalo, Italy; Fronlen, Wales; Bolia, Brazil; Magnet Cove, Arkansas; etc.

**DIAG.** The crystal form, the abnormally strong dispersion of the optic axes with consequent abnormal interference colors, the extremely high refringence and birefringence are characteristic.

**Tellurite** ( $TeO_2$ ) is orthorhombic dipyramidal with  $a:b:c = 0.456:1:0.469$ . Space group  $^{64}Pcab$ ;  $a$  5.50,  $b$  11.75,  $c$  5.59 Å. U.C. 8. Crystals {010} plates, often elongated parallel to  $c$ ; perfect 010 cleavage. Flexible. H. = 2. G. = 5.9. Fusible. Soluble in  $NH_4OH$ . The optic plane is 100;  $X = b$ .  $(+?)2V = 90^\circ \pm$ ,  $r < v$  moderate.  $N_X = 2.00$ ,  $N_Y = 2.18$ ,  $N_Z = 2.35$ ,  $N_Z - N_X = 0.35$ . Colorless, white, or yellow in mass; colorless in section. Artificial crystals of  $TeO_2$  formed at low temperature are tetragonal with  $c = 0.554$ . Tellurite is found with native tellurium as an oxidation product, as in Boulder County, Colorado.

**Cervantite** ( $Sb_2O_4?$ ) is orthorhombic(?); crystals acicular or powdery. H. = 4-5. G. = 6.64 (artificial). F. = 7. Soluble in HCl. Artificial crystals of  $Sb_2O_4$  are orthorhombic  $^{65}$  with  $a$  4.804,  $b$  5.424,  $c$  11.76 Å. Space group  $Pna$ , but natural samples labeled cervantite are usually not homogeneous, have not been analyzed, and give widely different optical properties, as follows:  $^{66}N = 1.67, 1.71-1.75, 1.88, 1.91-1.97, 1.98$  ca., 2.05, with weak to strong birefringence and positive elongation. For example:  $N_X = 1.83$ ,  $N_Z = 2.04$ ,  $N_Z - N_X = 0.21$ , and  $(-)2V =$  small. Color yellow to white. An oxidation product of stibnite, etc., as in Sonora, Mexico, Blaine County, Idaho, etc.

**Ianthinite** ( $2UO_2 \cdot 7H_2O?$ ) is orthorhombic with  $a:b:c^{22} = 0.9996:1:1.2964$ . Rectangular plates with perfect 001 cleavage. H. = 2-3. Optic plane is 100;  $X = c$ .  $(-)2V =$  small,  $N_X = 1.674$ ,  $N_Y = 1.90$ ,  $N_Z = 1.92$ ,  $N_Z - N_X = 0.246$ . Color violet-black; alters to yellow. Streak brown-violet. In section dark violet with  $X =$  colorless,  $Y =$  violet,  $Z =$  dark violet. Found in the Belgian Congo.

**Epiianthinite**  $^{67}$  is similar; probably an alteration product of oxidation,  $UO_2$  becoming  $UO_3$ .  $(-)2V =$  very small,  $N_X = 1.70$ ,  $N_Y = 1.790$ ,  $N_Z = 1.793$ ,  $N_Z - N_X = 0.093$ .  $X(c) =$  pale yellow,  $Y(b) =$  yellow,  $Z(a) =$  deep yellow.

**Baddeleyite** ( $ZrO_2$ ) is monoclinic prismatic with  $a:b:c = 0.987:1:1.019$ ,  $\beta = 99^\circ 08'$ . Space group  $^{68}P2_1/c$ ;  $a$  5.21,  $b$  5.26,  $c$  5.37 Å,  $\beta = 80^\circ 32'$ . U.C. 4. Crystals often {100} tablets with 100 or 110 twinning, sometimes lamellar. Perfect basal cleavage. H. = 6.5. G. = 5.4-6.0. F. = 6. Decomposed by  $H_2SO_4$ . Optic plane is 010;  $X \wedge c = -12^\circ$ .  $(-)2V = 30^\circ$ ,  $r > v$ , rather strong.  $N_X = 2.13$ ,  $N_Y$

$^{64}$  T. Ito: *Min. Abst.*, VI, 43 (1935).

$^{65}$  K. Dählström: *Zeit. anorg. Chem.*, CCXXXIX, 57 (1938).

$^{66}$  E. S. Larsen: *U. S. Geol. Surv. Bull.* 679 (1921) and 848 (1934).

$^{67}$  A. Schoep and S. Steadlot: *Am. Mineral.*, XXXII, 344 (1947).

$^{68}$  F. Yeadley: *Mineral. Mag.*, XXI, 169 (1920).

= 2.19,  $N_Z = 2.20$ ,  $N_Z - N_X = 0.07$ . Colorless to black. Streak white to brownish. Brown (to colorless) in section with  $X = \text{yellow}$ , brown, or green,  $Y = \text{green}$  or brown,  $Z = \text{brown}$  or light brown, and  $X > Y > Z$ . Inverts to tetragonal phase at about  $1000^\circ \text{C}$ .; other phases known. Found in gem sands in Ceylon and Brazil.

### 5. Simple oxides with type formula $AX_3$

**Tungstite**<sup>69</sup> ( $\text{H}_2\text{WO}_4$ ?) is orthorhombic(?); composed of microscopic scales with one perfect cleavage, taken as basal.  $H. = 2.5$ .  $G. = 5.5(?)$ .  $F. = 7$ . Soluble in KOH, but not in acids.  $X$  normal to cleavage.  $(-)2V = 26^\circ$ ,  $r < v$  distinct.  $N_X = 2.09$ ,  $N_Y = 2.24$ ,  $N_Z = 2.26$ ,  $N_Z - N_X = 0.17$ ; <sup>70</sup> again:  $N_X = 1.82$ ,  $N_Y = ?$ ,  $N_Z = 2.04$ ,  $N_Z - N_X = 0.22$ . Color golden yellow to green. Luster pearly. Some crystals show absorption with  $X < Y < Z$ . Found at Oruro, Bolivia; Salida, Colorado; etc.

**Schoepite**<sup>72</sup> ( $4\text{UO}_3 \cdot 9\text{H}_2\text{O}$ ?) is orthorhombic dipyramidal with  $a:b:c = 0.852:1:0.875$ .  $a$  14.40,  $b$  16.89,  $c$  14.75 Å. U.C. 8(?). Crystals {001} tablets or prismatic complex, with perfect 001 cleavage.  $H. = 2-3$ .  $G. = 4.8$ . Optic plane is 010;  $X = c$ .  $(-)2V = 89^\circ$ ,  $r > v$ .  $N_X = 1.690$ ,  $N_Y = 1.714$ ,  $N_Z = 1.735$ ,  $N_Z - N_X = 0.045$ . Color and streak yellow with  $X = \text{colorless}$ ,  $Y$  and  $Z = \text{lemon yellow}$ . Found in Belgian Congo.

**Paraschoepite**<sup>68</sup> ( $5\text{UO}_3 \cdot 9.5\text{H}_2\text{O}$ ) is orthorhombic but has  $(-)2V = 40^\circ$ ,  $r > v$ , and  $N_X = 1.705$ ,  $N_Y = 1.760$ ,  $N_Z = 1.770$ ,  $N_Z - N_X = 0.065$ .  $X = c$ .  $Y = b$ . Closely similar to schoepite.

**Becquerelite** ( $3\text{UO}_3 \cdot 5\text{H}_2\text{O}$ ?) is orthorhombic dipyramidal with  $a:b:c = 0.939:1:0.831$ . Space group <sup>71</sup>  $Pnam$ ;  $a$  13.93,  $b$  14.84,  $c$  12.34 Å. Crystals {010} tablets; massive; perfect 010 cleavage. Twinning on 101.  $H. = 2-3$ .  $G. = 5.09$ . Optic plane is 001;  $X = b$ .  $(-)2V = 30^\circ 35' \text{Na}$ ,  $r > v$ . The optic angle decreases with heat, and the mineral is uniaxial above  $100^\circ \text{C}$ .  $N = 1.730$ ,  $N_Y = 1.822$ ,  $N_Z = 1.830$ ,  $N_Z - N_X = 0.095$ . A sample containing some Pb has: <sup>72</sup>  $N_X = 1.75$ ,  $N_Y = 1.87$ ,  $N_Z = 1.88$ ,  $N_Z - N_X = 0.13$ . Color dark amber-yellow with  $X = \text{colorless}$ ,  $Y$  and  $Z = \text{yellow}$ , and  $X < Y < Z$ . Found in the Belgian Congo.

**Billietite** is chemically related to becquerelite,<sup>73,74</sup> but contains some Ba. It is orthorhombic,<sup>75</sup> with  $a:b:c = 0.603:1:1.271$ . Perfect 001 cleavage. Pseudo-hexagonal twinning on 110.  $X = c$ ,  $Z = b$ .  $(-)2V = 36^\circ$ ,  $N_X = 1.74$ ,  $N_Y \approx N_Z \approx 1.77$ ,  $N_Z - N_X \approx 0.03$ .  $X = \text{almost colorless}$ ,  $Y = \text{greenish yellow}$ ,  $Z = \text{amber-brown}$ . Found in Katanga.

**Masuyite**<sup>73,74</sup> contains  $\text{UO}_3$ ,  $\text{PbO}$ , and  $\text{H}_2\text{O}$ . It forms pseudo-hexagonal orthorhombic {010} scales, twinned on 010. Good 010 cleavage.  $X = b$ ,  $Z = c$ .  $(-)2V = \text{large}$ ,  $N_Y$  and  $N_Z$  between 2.11 and 2.15. Found in Katanga, Belgian Congo.

<sup>69</sup> P. F. Kerr and F. Young: *Am. Mineral.*, XXIX, 192 (1944), show that formula of tungstite is probably  $\text{H}_2\text{WO}_4$  and of hydrotungstite  $\text{H}_2\text{WO}_4 \cdot \text{H}_2\text{O}$ .

<sup>70</sup> T. L. Walker: *Am. Jour. Sci.*, CLXXV, 305 (1908).

<sup>71</sup> H. Brasseur: *Am. Mineral.*, XXXIII, 619 (1948);  $b$  and  $c$  interchanged to make  $b > a > c$ .

<sup>72</sup> V. Billiet: *Bull. Soc. Fr. Min.*, XLIX, 136 (1926).

<sup>73</sup> A. Schoep and S. Stradiot: *Am. Mineral.*, XXXIII, 503 (1948).

<sup>74</sup> J. F. Vaes: *Min. Abst.*, X, 146 (1947).

<sup>75</sup> J. Thoreau: *Bull. Soc. Géol. Belg.*, LXXI, B76 (1948).

**Richetite** <sup>73,74</sup> contains  $UO_3$ ,  $PbO$ , (and  $H_2O$ ?). It forms pseudo-hexagonal monoclinic {010} plates. Good 010 cleavage. Extinction at  $6^\circ$  on 010.  $(- )2V$  = large,  $N_Y$  and  $N_Z$  between 2.00 and 2.07. Mass color black. Found in Katanga.

**Hydrotungstite** <sup>69</sup> ( $H_2WO_4 \cdot H_2O$ ?) is monoclinic(?) with poor 010 cleavage. Crystals platy. Multiple twinning on  $1\bar{1}0$  very common.  $H. = 2$ .  $G. = 4.6$ . Soluble in  $NH_4OH$ , but not in acids. Optic plane is 010;  $X \wedge \perp 001 = 3^\circ$ .  $(- )2V = 52^\circ \pm$ ,  $N_X = 1.70$ ,  $N_Y = 1.95$ ,  $N_Z = 2.04$ ,  $N_Z - N_X = 0.34$ . Color green with  $X$  = colorless,  $Y$  = yellow-green,  $Z$  = dark green. Found in Bolivia as an alteration product of ferberite.

**Gummite** ( $UO_3 \cdot nH_2O$ ) is a name applied to alteration products of uraninite, doubtless a whole series, and often a mixture. Always contains  $PbO$  and  $H_2O$ , and usually rare earths, etc. Fine-grained but not isotropic, Conchoidal to uneven fracture.  $H. = 2.5-5$ .  $G. = 3.9-6.4$ .  $F. = 7$ . Soluble in acid. Optic properties vary widely, for example:

$(- )2V$	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$	Locality
$30-50^\circ r < v$	1.997	2.098	2.108	0.111	North Carolina <sup>76</sup> ( <i>clarkeite</i> )
$60^\circ r < v$	1.742	1.762	1.776	0.034	North Carolina <sup>76</sup>

$N = 1.96$  Katanga;<sup>77</sup>  $N = 1.61$  (locality?);<sup>78</sup>  $N = 1.575$  Easton, Pennsylvania.<sup>78</sup>

Color orange-red; dark reddish brown (*clarkeite*); yellow with little or no pleochroism in section. Found with uraninite, as at Easton, Pennsylvania.

## B. HYDROXIDES

In this division are included some oxides containing hydroxyl and also certain hydrated carbonate-hydroxides.

### 1. Hydroxides with type formula $AX_2$

**BRUCITE** HEXAGONAL SCALENOHEDRAL  $c/a = 1.521$   $Mg(OH)_2$

**COMP.** May contain at least 18%  $MnO$ , 10%  $FeO$ , some  $ZnO$ ,  $Fe_2O_3$ , etc.

**STRUC.** Space group <sup>79</sup>  $C\bar{3}m$ ;  $a$  3.125,  $c$  4.75; hexagonal U.C. 1.

**PHYS. CHAR.** Crystal basal plates; often foliated massive; also fibrous. Micaceous basal cleavage; flexible and sectile.  $H. = 2.5$ .  $G. = 2.4$ .  $F. = 7$ . Soluble in  $HCl$ .

**OPT. PROP.** Uniaxial and positive; fibrous types (called *nemalite*) distinctly biaxial, the fibers being elongated parallel to a diagonal of the base, with  $X$  parallel to the elongation. Heat <sup>80</sup> reduces  $2V$ . Nemalite

<sup>76</sup> C. S. Ross, E. P. Henderson, and E. Posnjak: *Amer. Mineral.*, XVI, 213 (1931).

<sup>77</sup> A. Schoep and L. de Leenheer: *Bull. Soc. Belge Géol.*, XLVI, 309 (1937).

<sup>78</sup> R. C. Wells, J. G. Fairchild, and C. S. Ross: *Am. Jour. Sci.*, CCXXVI, 45 (1933).

<sup>79</sup> G. Aminoff: *Zeit. Krist.*, LVI, 506 (1921), and J. Garrido: *Zeit. Krist.*, XCV, 189 (1936).

<sup>80</sup> C. Doelter: *N. Jahrb. Min.*, II, 217 (1882).



with 8%  $\text{Fe}(\text{OH})_2$  and 1.5% of magnetite inclusions has form birefringence<sup>81</sup> and  $N_O = 1.589$ ,  $N_E = 1.585$ ,  $N_O - N_E = 0.004$ . Indices of brucite:<sup>82</sup>

$\lambda$	706.5	587.6	501.6	471.3	447.1	F - C (calc.)
$N_E$	1.5815	1.5853	1.5902	1.5927	1.5949	0.0084
$N_O$	1.5617	1.5662	1.5730	1.5764	1.5794	0.0117
$N_E - N_O$	0.0198	0.0191	0.0172	0.0163	0.0155	0.0033

With<sup>83</sup> 18.1 MnO and 3.7 ZnO,  $N_E = 1.60$ ,  $N_O = 1.59$ . See Fig. 44.

Color white, greenish, brownish (with Fe or Mn); colorless in section. Luster pearly.

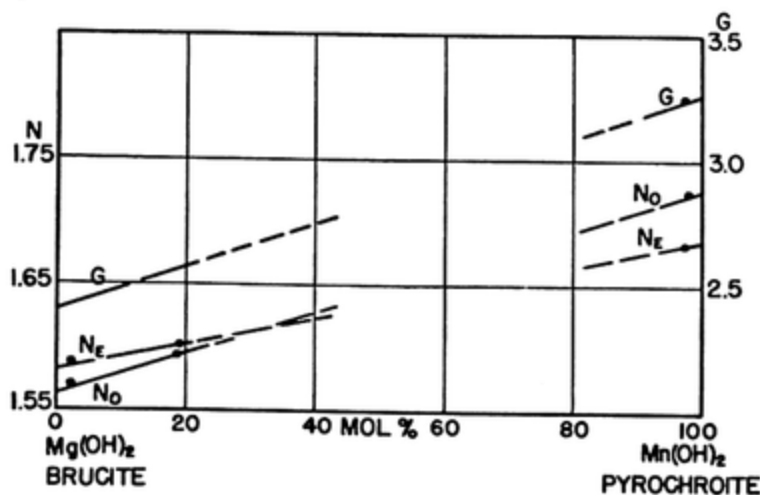


FIG. 44. Properties of the brucite-pyrochroite discontinuous series.

**ALTER.** Often an alteration product of periclase; alters readily to hydromagnesite; rarely to serpentine.

**OCCUR.** A hydrothermal mineral in serpentine and periclase limestones and dolomites.

**DIAG.** Brucite has better cleavage than alunite and flexible lamellae; it differs from talc, muscovite, and gypsum in being uniaxial and positive, and from hydromagnesite and white chlorite (*leuchtenbergite*) in having stronger birefringence.

**Pyrochroite**  $[\text{Mn}(\text{OH})_2]$  is hexagonal scalenohedral.  $c/a = 1.401$ ; space group<sup>84</sup>  $C\bar{3}m$ ;  $a$  3.34,  $c$  4.68 Å. U.C. 1. Crystals platy with perfect basal cleavage.  $H. = 2.5$ .  $G. = 3.25$ .  $F. = 7$ . Soluble in HCl. Uniaxial negative, or slightly biaxial, with  $N_O = 1.723$ ,  $N_E = 1.681$ ,  $N_O - N_E = 0.042$ ;<sup>85</sup>  $N_O = 1.733$ ,  $N_O - N_E = 0.04$ .<sup>86</sup>

<sup>81</sup> J. D. H. Donnay: *Univ. Toronto Stud., Geol. Ser.*, 49, 5 (1945).

<sup>82</sup> O. Westphal in Ehringhaus: *N. Jahrb. Min., Bl. Bd. XLI*, 371 (1917).

<sup>83</sup> L. H. Bauer and H. Berman: *Am. Mineral.*, XV, 340 (1930).

<sup>84</sup> G. Aminoff: *Geol. För. Förh. Stockholm*, XLI, 407 (1919).

<sup>85</sup> H. Sjögren: *Geol. För. Förh. Stockholm*, XXVII, 37 (1905).

<sup>86</sup> A. F. Rogers: *Am. Jour. Sci.*, CXCVIII, 443 (1919).



Colorless to yellow or brown and pleochroic with  $O > E$ . Luster pearly. A hydrothermal mineral, as at Persberg, Sweden; Franklin, New Jersey; etc.

**Portlandite**<sup>87</sup>  $[Ca(OH)_2]$  is hexagonal scalenohedral with  $c/a = 1.365$ . Space group  $C\bar{3}m$ ;  $a$  3.585,  $c$  4.895 Å. U.C. 1; crystals minute plates with perfect basal cleavage.  $H. = 2$ .  $G. = 2.23$ . Soluble in weak HCl. Uniaxial negative with  $N_O = 1.575$ ,  $N_E = 1.547$ ,  $N_O - N_E = 0.028$ . Colorless. Pearly luster. Alters easily to  $CaCO_3$ . Found with awillite and calcite at Scawt Hill, Ireland.

**Pyroaurite**  $[Mg_6Fe_2'''(OH)_{16}CO_3 \cdot 4H_2O]$  is rhombohedral<sup>88</sup> with  $c/a = 7.519$ .  $a$  6.19,  $c$  46.54 Å. U.C. 3. (A variety<sup>89</sup> with 5–6%  $Cr_2O_3$  is known.) Crystals basal plates with perfect basal cleavage.  $H. = 2-3$ .  $G. = 2.12$ .  $F. = 7$ . Soluble in acid with effervescence. Uniaxial negative with  $N_O = 1.560-1.567$ ,  $N_E = 1.543$  ca.  $N_O - N_E = 0.02$  ca. Color brown to white with  $E =$  colorless,  $O =$  yellow to brown; sometimes biaxial with 2V small. Found at Långban, Sweden.

**Hydrotalcite**  $[Mg_6Al_2(OH)_{16}CO_3 \cdot 4H_2O]$  is rhombohedral<sup>88</sup> with  $c/a = 7.528$ .  $a$  6.13,  $c$  46.15 Å. U.C. 3. Crystals basal plates with perfect basal cleavage.  $H. = 2$ .  $G. = 2.06$ .  $F. = 7$ . Soluble in acid with effervescence. Uniaxial negative with  $N_O = 1.51-1.518$ ,  $N_E = 1.494$ ,  $1.504$ ,  $N_O - N_E = 0.012-0.017$ . Also biaxial,<sup>90</sup> probably owing to strain, with 2V small. Color white with pearly luster. An alteration product of spinel, found at Snarum, Norway.

**Stichtite**<sup>91</sup>  $[Mg_6Cr_2(OH)_{16}CO_3 \cdot 4H_2O]$  is rhombohedral<sup>88</sup> with  $c/a = 7.505$ ,  $a$  6.18,  $c$  46.38 Å. U.C. 3. Basal plates with perfect basal cleavage.  $H. = 1.5-2$ .  $G. = 2.16$ .  $F. = 7$ . Soluble in acid with effervescence. Uniaxial negative with  $N_O = 1.542-1.545$ ,  $N_E = 1.516-1.518$ ,  $N_O - N_E = 0.026-0.027$ . In part biaxial,<sup>92</sup> due to strain. Color lilac to pink and weakly pleochroic with  $O > E$ . Found at Dundas, Tasmania.

**Brugnatellite**<sup>91</sup>  $[Mg_6F'''(OH)_{13}CO_3 \cdot 4H_2O]$  is hexagonal<sup>88</sup> with  $c/a = 2.92$ .  $a$  5.47,  $c$  15.97 Å. U.C. 4. Perfect basal cleavage.  $H. = 2$ .  $G. = 2.14$ .  $F. = 7$ . Soluble in acid with effervescence. Uniaxial negative with  $N_O = 1.533-1.540$ ,  $N_E = 1.510$ ,  $N_O - N_E = 0.030$  (also reported as "weak"). With increasing iron content  $N_O$  varies from 1.565 to 1.605.<sup>93</sup> Color light pink or yellow with  $O =$  yellowish red,  $E =$  colorless. Found in serpentine in Lombardy, Italy.

**Sjögrenite**  $[Mg_6Fe_2'''(OH)_{16}CO_3 \cdot 4H_2O]$  is hexagonal<sup>88</sup> with  $c/a = 2.511$ .  $a$  6.20,  $c$  15.57 Å. Crystals basal plates with basal cleavage and pearly luster.  $H. = 2.5$ .  $G. = 2.11$ . Uniaxial negative with  $N_O = 1.573$ ,  $N_E = 1.550$ ,  $N_O - N_E = 0.023$ . Color white to yellowish with  $O =$  pale yellow to brownish,  $E =$  colorless. A hydrothermal product; known only at Långban, Sweden.

**Manasseite**  $[Mg_6Al_2(OH)_{16}CO_3 \cdot 4H_2O]$  is hexagonal<sup>88</sup> with  $c/a = 2.507$ ,  $a$  6.12,  $c$  15.34 Å. Found in contorted lamellar masses or fibers. Perfect basal cleavage with pearly luster.  $H. = 2$ .  $G. = 2.05$ . Uniaxial negative with  $N_O = 1.524$ ,  $N_E = 1.510$ ,  $N_O - N_E = 0.014$ . Also biaxial with 2V = small. Color white or pale bluish. Found at Snarum and Kongsberg, Norway, and Amity, New York.

<sup>87</sup> C. E. Tilley: *Mineral. Mag.*, XXIII, 419 (1933).

<sup>88</sup> C. Frondel: *Am. Mineral.*, XXVI, 295 (1941).

<sup>89</sup> S. Caillère: *C. R. Acad. Sci. Paris*, CCXV, 420 (1942).

<sup>90</sup> S. Caillère: *C. R. Acad. Sci. Paris*, CCXIX, 256 (1944).

<sup>91</sup> S. Caillère (*Bull. Soc. Fr. Min.*, LXVI, 494, 1943) gives  $9MgO \cdot Cr_2O_3 \cdot 2CO_2 \cdot 18H_2O$  and  $9MgO \cdot Fe_2O_3 \cdot 2CO_2 \cdot 18H_2O$  as formulas of stichtite and brugnatellite.

<sup>92</sup> S. Caillère (*C. R. Acad. Sci. Paris*, CCXV, 215, 1942) found lamellae with  $Z \parallel$  elongation and  $N_X = 1.543$ ,  $N_Z = 1.562$ .

<sup>93</sup> A. I. Kiselev: *Min. Abst.*, IX, 267 (1946).

**Barbertonite**  $[\text{Mg}_6\text{Cr}_2(\text{OH})_{16}\text{CO}_3 \cdot 4\text{H}_2\text{O}]$  is hexagonal<sup>88</sup> with  $c/a = 2.515$ ,  $a$  6.17,  $c$  15.52 Å. Contorted lamellar masses or fibers with perfect basal cleavage.  $H. = 1.5-2$ .  $G. = 2.10$ . Uniaxial negative with  $N_O = 1.557$ ,  $N_E = 1.529$ ,  $N_O - N_E = 0.028$ . Also biaxial with  $2V = \text{small}$ . Color rose-pink to violet. Weak pleochroism with  $O > E$ . Found at Dundas, Tasmania, and Barberton, Transvaal.

**Lepidocrocite**  $[\text{FeO}(\text{OH})]$  is orthorhombic dipyramidal<sup>94</sup> with  $a:b:c = 0.309:1:0.245$ ; space group  $Cmcm$ ;  $a$  3.87,  $b$  12.51,  $c$  3.06 Å. U.C. 4. Crystals scaly parallel to 010 with perfect 010 and inferior 100 and 001 cleavages.  $H. = 5$ .  $G. = 4.09$ . Optic plane is 001;  $X = b$ .  $(- )2V = 83^\circ$ , with weak dispersion.  $N_X = 1.94$ ,  $N_Y = 2.20$ ,  $N_Z = 2.51$ ,  $N_Z - N_X = 0.57$ . Color blood red. Streak orange. Pleochroic with  $X = \text{nearly colorless to yellow}$ ,  $Y = \text{orange yellow to red-orange}$ ,  $Z = \text{brownish yellow to orange-red}$ , and  $X < Y < Z$ . In polished section gray white, strongly anisotropic and pleochroic. Reflection percentages:<sup>3</sup> red 16, orange 17, green 20.5. Found in iron-ore deposits with goethite, as at Easton, Pennsylvania. Differs from goethite in having much weaker dispersion, and in having maximum absorption parallel to the elongation.

**Boehmite**  $[\text{AlO}(\text{OH})]$  is orthorhombic dipyramidal with  $a:b:c = 0.320:1:0.242$ . Space group<sup>22,95</sup>  $Amam$ ;  $a$  3.78,  $b$  11.8,  $c$  2.85. U.C. 4. Crystals {001} tablets with 010 cleavage.  $H. = 3.5-4$ .  $G. = 3.0$ . Optic properties somewhat uncertain; probably  $Y = c$ ,  $Z = b$ ,  $(- )2V = \text{moderate}$ ,<sup>96</sup>  $N_X = 1.638$ ,  $N_Y = 1.645$ ,  $N_Z = 1.651$ ,  $N_Z - N_X = 0.013$ . Also reported<sup>97</sup> as  $X = a$ ,  $Z = c$ ,  $(+ )2V = 80^\circ$ ,  $N_X = 1.646$ ,  $N_Z = 1.661$ ,  $N_Z - N_X = 0.015$ . The indices decrease with loss of water caused by rising temperature;<sup>98</sup> thus  $N_X \approx N_Y \approx 1.632$ ,  $N_Z = 1.639$ , at room temperature and  $N = 1.625$  at  $348^\circ \text{C}$ . with  $12.5 \text{ H}_2\text{O}$ . Dehydration<sup>97</sup> finally gives:  $X = b$ ,  $Y = c$ ,  $Z = a$ , and  $(- )2V = 54^\circ$ ,  $N_X = 1.581$  calc.,  $N_Y = 1.582$ ,  $N_Z = 1.587$ ,  $N_Z - N_X = 0.006$ . Found in bauxite ores as at Ariège, France; Ayrshire, Scotland; and Berger, Arkansas.

**Manganite**  $[\text{MnO}(\text{OH})]$  is monoclinic prismatic<sup>99</sup> with  $a:b:c = 0.844:1:0.545$ ,  $\beta = 90^\circ 0'$  (pseudo-orthorhombic). Space group  $B2_1/d$ ;  $a$  8.86,  $b$  5.24,  $c$  5.70 Å. U.C. 8. Crystals usually have many faces; striations parallel to  $c$  common. Twinning on 011. Perfect 010 and good 110 and 001 cleavages.  $H. = 4$ .  $G. = 4.3$ .  $F. = 7$ . Soluble in  $\text{HCl}$ . Nearly opaque; optic plane is 010;  $Z = c$  (Larsen);  $Z \wedge c = 4^\circ$ ;<sup>100</sup>  $(+ )2V = \text{small}$ ,  $r > v$  very strong.  $N_X = 2.25$  (2.23),  $N_Y = 2.25$ ,  $N_Z = 2.53$  Li,  $N_Z - N_X = 0.28$ . Color steel gray to iron black. Streak dark reddish brown. Luster submetallic. Pleochroic in section, red-brown to brownish yellow and weakly pleochroic with  $X$  and  $Y < Z$ . In polished section grayish white with a brownish tint; strongly anisotropic. Reflection percentages,<sup>3</sup>  $\parallel a$ : red 12.5, orange 12, green 16;  $\parallel c$ : red 15.5, orange 16, green 19. Alters readily to pyrolusite. Hydrothermal vein mineral; associated with pyrolusite, goethite, etc. Among manganese minerals it is distinguished by its crystal form, easy cleavage, streak, and frequent fibrous or lamellar state.

<sup>94</sup> F. J. Ewing: *J. Chem. Phys.*, III, 420 (1935).

<sup>95</sup> P. P. Reichertz and W. J. Yost: *J. Chem. Phys.*, XIV, 495 (1946).

<sup>96</sup> J. de Lapparent: *Bull. Soc. Fr. Min.*, LVIII, 246 (1935). Also Nieuwenburg and Peters: *Rec. Trav. Chim. Pays-Bas*, XLVIII, 32 (1929).

<sup>97</sup> E. M. Bohnstedt-Kupletskaya: *Min. Abst.*, X, 144 (1947).

<sup>98</sup> H. Schwierisch: *Chem. Erde*, VIII, 252 (1933). H. Achenbach's work (*Chem. Erde*, VI, 307 (1931) agrees with this.

<sup>99</sup> M. J. Buerger: *Zeit. Krist.*, XCV, 163 (1936).

<sup>100</sup> O. Mügge: *Cent. Min.*, 1922, 1.

## 2. Hydroxides with type formula $AX_3$

**GIBBSITE** (*Hydrargillite*) MONOCLINIC PRISMATIC

$Al(OH)_3$

$$a:b:c = 1.709:1:1.918 \quad \beta = 94^\circ 31'$$

STRUC. Space group  $^{101}P2_1/n$ ;  $a$  8.624,  $b$  5.060,  $c$  9.699,  $\beta = 94^\circ 34'$ . U.C. 8.

PHYS. CHAR. Crystals uncommon, six-sided {001} tablets; often finely lamellar; also in concretions or crusts. Micaceous 001 cleavage. Percussion figures similar to those of the micas. Twinning common on 001 and on 130, often multiple and complex.  $H. = 3$ .  $G. = 2.3-2.4$ .  $F. = 7$ . Soluble in  $H_2SO_4$ . Has an argillaceous odor. Soluble in hot  $NaOH$ , from which it recrystallizes on cooling.

OPT. PROP. The variations in optic properties reported by different writers may be due to the effects of temperature (changing the  $H_2O$  content?), since heat has a marked effect on the optic angle and may change the optic orientation. In most crystals the optic plane and  $X$  are normal to 010;  $^{102}Z \wedge c = +21^\circ$ . See Fig. 45. The optic angle decreases with rise of temperature becoming  $0^\circ$  at  $26.5^\circ C$ . (for blue); above that temperature the optic plane is 010 for all light above  $56^\circ$ ;  $Z \wedge c = -45^\circ$  Li in crystals from the Urals.<sup>103</sup> Upon cooling the changes are reversed. In nature the mineral occurs with any of the positions thus produced by heat. The optic angle is always small and may be  $0^\circ$ . When fibrous, the elongation is  $\pm$ , and extinction is inclined.

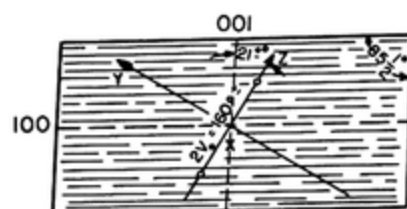


FIG. 45. The optic orientation of gibbsite.

(+) $2V = 0^\circ-20^\circ \pm r > v$  strong (optic plane normal to 010)

(+) $2V = 0^\circ-20^\circ \pm r < v$  strong (optic plane parallel to 010).

$N_X \approx N_Y$	$N_Z$	$N_Z - N_X$	Locality	Author
1.565	1.58	0.015	Kussinsk, Urals	Larsen <sup>66</sup>
1.566	1.585	0.019	Chester, Massachusetts	Larsen <sup>66</sup>
1.570	1.586	0.016	Urals	Polyanin <sup>104</sup>
1.571	1.59	0.019	Brazil	Lacroix <sup>105</sup>
1.565	1.595	0.03	Dundas, Tasmania	Larsen <sup>66</sup>
1.577	1.595	0.018	Artificial	Achenbach <sup>106</sup>

Color white, grayish, greenish, reddish. Colorless in section.

OCCUR. Abundant in bauxite deposits in America. It is a common decomposition product of feldspar and also of corundum.

DIAG. Distinguished from kaolinite by stronger birefringence, from muscovite by optic sign and inclined extinction, from brucite and wavellite by inclined extinction and chemical reactions.

<sup>101</sup> H. D. Megaw: *Zeit. Krist.*, LXXXVII, 185 (1934).

<sup>102</sup> W. C. Brögger: *Zeit. Kryst.*, XVI, 16 (1890).

<sup>103</sup> A. Des Cloizeaux: *Inst. Imp. France Mém.*, 18 (1867).

<sup>104</sup> V. A. Polyanin: *Min. Abst.*, VII, 440 (1940).

<sup>105</sup> A. Lacroix: *Min. France*, III, 363 (1901).

<sup>106</sup> H. Achenbach: *Chem. Erde*, VI, 307 (1931).

**Bauxite** is a name applied to an aggregate of minerals which are largely hydrous aluminum oxides, especially gibbsite, boehmite, diaspore, and amorphous hydrated alumina; any one of these many be dominant. Bauxite, like other rocks, normally contains minor quantities of other minerals, especially limonite, quartz, feldspar, zircon, etc. By increase in content of limonite, bauxite grades into laterite. Bauxite is typically concretionary and probably always at least in part colloidal.  $G.$  = about 2.55.  $N = 1.56$  ca. to 1.61 ca. Color gray, yellow, white, brown, varying with tenor of limonite. It is the chief aluminum ore. It differs from clay in not making a paste with water.

**Sassolite**  $[B(OH)_3]$  is triclinic pinacoidal with <sup>22</sup>  $a:b:c = 0.999:1:0.923$ ,  $\alpha = 92^\circ 30'$ ,  $\beta = 101^\circ 11'$ ,  $\gamma = 119^\circ 51'$ . Space group <sup>107</sup>  $P\bar{1}$ ;  $a$  7.04,  $b$  7.04,  $c$  6.56; U.C. 4. Crystals basal plates, six-sided; also scaly, stalactitic; twinning about  $c$ . Perfect basal cleavage.  $H. = 1$ .  $G. = 1.48$ .  $F. = 0.5$ . Soluble in  $H_2O$ . Optic plane nearly parallel to axis  $b$  and  $X$  nearly normal to 001. Extinction angle on 010 to  $c$  is  $12^\circ$  to  $13^\circ$ , <sup>108</sup> or  $3-4^\circ$ ; <sup>109</sup> on 001 to  $b$  is  $2.5$  to  $20^\circ$ ; on 110 to  $c$  is  $12-13^\circ$ . Basal plates weakly birefringent.  $(- )2V = (0^\circ-7^\circ)$  without visible dispersion.  $N_X = 1.340$ ,  $N_Y = 1.456$ ,  $N_Z = 1.459$ ,  $N_Z - N_X = 0.119$ . Color white or grayish. Found in Tuscan lagoons; also about volcanoes. Fused sassolite ( $B_2O_3$ ) has  $N = 1.4637$  Na.

## C. MULTIPLE OXIDES

The multiple oxides <sup>110</sup> include minerals previously classed as oxides and others previously considered as manganates, aluminates, ferrates, columbates, tantalates, zirconates, titanates, uranates, vanadates. They are arranged, first, on the basis of the  $A + B$  to  $X$  ratio, and second, on the  $A$  to  $B$  ratio.

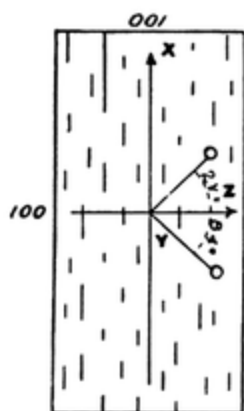


FIG. 46. The optic orientation of diaspore.

### 1. Multiple oxides with type formula $ABX_2$

**DIASPORE** ORTHORHOMBIC DIPYRAMIDAL  $HAIO_2$   
 $a:b:c = 0.469:1:0.302$

**COMP.** Diaspore differs from boehmite in having no hydroxyl group, but instead having  $H$  as a cation between two oxygen atoms.

**STRUC.** Space group <sup>111</sup>  $Pbnm$ ;  $a$  4.40,  $b$  9.39,  $c$  2.84 Å. U.C. 4.

**PHYS. CHAR.** Crystals {010} tablets, prismatic, with perfect 010 and distinct 110 cleavages.  $H. = 6.5-7$ .  $G. = 3.3-3.5$ .  $F. = 7$ . Insoluble in acids, but soluble in  $H_2SO_4$  after calcination. Soluble in hot  $NaOH$ .

**OPT. PROP.** The optic plane is 010 and  $Z = a$ . See Fig. 46.  $(+)2V = 84^\circ 20'$ ,  $r < v$  weak.  $N_X = 1.702$  Na,  $N_Y = 1.722$ ,  $N_Z = 1.750$ ,  $N_Z - N_X = 0.048$ .  $F - C$  for  $N_Y = 0.0089$  <sup>112</sup> and for  $N_X = 0.0073$ . Color white, gray, colorless;

<sup>107</sup> W. H. Zachariasen: *Zeit. Krist.*, LXXXVIII, 150 (1934).

<sup>108</sup> K. Haushofer: *Zeit. Kryst.*, IX, 77 (1884).

<sup>109</sup> D'Achiardi: *N. Jahrb. Min.*, 1902, I, 170.

<sup>110</sup> The usage of Dana's *System of Mineralogy*, 7th Ed., is here followed, except that all the multiple oxides are grouped together.

<sup>111</sup> F. J. Ewing: *J. Chem. Phys.*, III, 203 (1935).

<sup>112</sup> E. Gübelin: *Schw. Min. Pet. Mit.*, XIX, 325 (1940).

rarely brown, yellow, pink, etc. Usually colorless in section, but also (with  $Mn^{III}$  or  $Fe^{III}$ ):  $X$  = dark violet or reddish brown,  $Z$  = yellowish white; also  $X = Y$  = colorless,  $Z$  = blue; blue and green rare.

**OCCUR.** Often associated with corundum; also found in volcanic rocks with alunite; also in various schists. Common in bauxite deposits.

**DIAG.** Among lamellar minerals distinguished by the position of the optic plane parallel to the cleavage and by strong birefringence; also by insolubility, hardness, and specific gravity.

## GOETHITE

ORTHORHOMBIC DIPYRAMIDAL <sup>113</sup>



$$a:b:c = 0.462:1:0.303$$

**COMP.** Goethite differs from lepidocrocite in having no hydroxyl, but instead H between two oxygen atoms.

**STRUC.** Space group  $Pbnm$ ;  $a$  4.587,  $b$  9.937,  $c$  3.015 Å. U.C. 4.

**PHYS. CHAR.** Crystals vertically striated prisms; also scaly, or tabular parallel to 010, or, rarely, 100; perfect 010 cleavage.  $H. = 5-5.5$ .  $G. = 3.3-4.3$  (massive); 4.28 (crystals).  $F. = 5.5$ . Soluble in HCl.

**OPT. PROP.** Goethite has extreme dispersion of the optic axes so that the optic plane is 100 for red, the optic angle is  $0^\circ$  for about 620 mμ, and the optic plane is 001 for yellow, green, and blue in the common condition. See Figs. 47, 48. The acute bisectrix, normal to 010, is negative for all colors, giving positive elongation of plates. The indices are:

	Bailly <sup>114</sup>					Merwin <sup>115</sup>
$\lambda = 850$	700	645	589	542		589
$N_X = 2.185$	2.234	2.247	2.275	2.303		2.260
$N_Y = 2.292$	2.344	2.371	2.409	2.439		2.393
$N_Z = 2.304$	2.356	2.378	2.415	2.447		2.398
$N_Z - N_X = 0.119$	0.122	0.131	0.140	0.144		0.138
$(- )2V = 36^\circ$	$26^\circ$	$17^\circ$	$23^\circ$	$25^\circ$		

At  $24^\circ$  C. the optic angle <sup>116</sup> is:

$\lambda = 691$	644	613	578	546	530
$(- )2E = 76^\circ$	$54^\circ$	$0^\circ$	$62^\circ$	$117^\circ$	$180^\circ$
Optic Plane 100			Optic Plane 001		

For constant wave length, increase of temperature causes the optic angle in 001 to decrease rapidly, become zero, and open again in 100. Thus for  $\lambda = 590$ ,  $2E = 85^\circ$  at  $0^\circ$  C.  $55^\circ$  at  $25^\circ$ , and  $22^\circ$  at  $43^\circ$ .

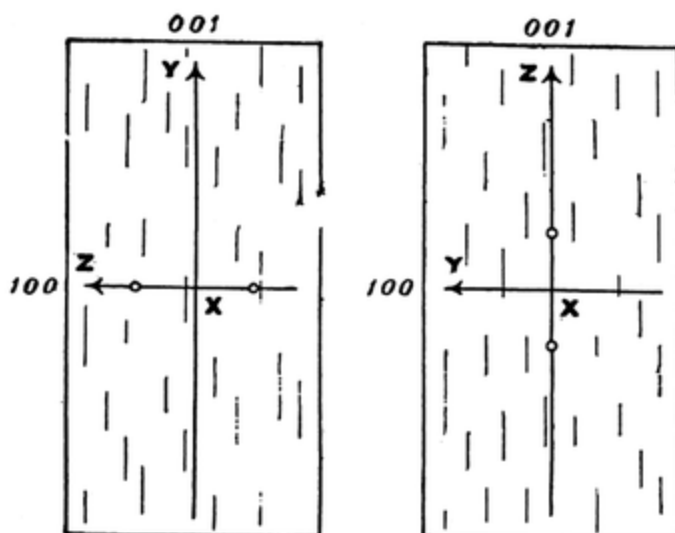
<sup>113</sup> M. A. Peacock: *Trans. Roy. Soc. Canada*, XXXVI, sect. 4, 107 (1942). S. Goldsztaub: *Comp. Rend. Acad. Sci. Paris*, CXCI, 533 (1931), and CXCV, 964 (1932).

<sup>114</sup> R. Bailly: *Am. Mineral.*, XXXIII, 519 (1948).

<sup>115</sup> H. E. Merwin: *Am. Jour. Sci.*, CXCVII, 311 (1919).

<sup>116</sup> W. M. D. Bryant in M. A. Peacock: *Univ. Toronto Geol. Stud.*, 49, 73 (1945).





FIGS. 47, 48. The optic orientation of goethite for red and blue light.

The mineral is often fibrous and impure with adsorbed water, etc., and then  $N_X = 2.05\text{--}2.21$ ,  $N_Y = 2.10\text{--}2.35$ ,  $N_Z = 2.11\text{--}2.35+$ ,  $N_Z - N_X = 0.06\text{--}0.14$ . As an example, fibrous goethite from Thuringia<sup>117</sup> has:  $N_X = 2.217$ ,  $N_Y = 2.346$ ,  $N_Z = 2.356$ ,  $N_Z - N_X = 0.139$ .

Color brown, yellowish, reddish. Streak yellow. In thin section variable pleochroism with  $a > c > b$  and  $X$  = clear yellow to brown,  $Y$  = brownish yellow,  $Z$  = orange-yellow. In polished section gray and strongly anisotropic. Reflection percentages:<sup>3</sup> red 13, orange 14, green 17.5.

**OCCUR.** Goethite is a very common mineral, forming much of the so-called limonite iron ore, and the usual product of weathering of iron minerals such as siderite, pyrite, magnetite, glauconite, and iron silicates.

**DIAG.** Goethite differs from hematite by its yellow streak and from lepidocrocite by its abnormally strong dispersion.

**Limonite** ( $\text{Fe}_2\text{O}_3 \cdot n\text{H}_2\text{O}$ ) is a general designation for hydrous iron oxide. It is usually apparently amorphous, but much of it is actually cryptocrystalline goethite (as proved by X-ray tests). Commonly massive and vitreous or pitchlike; also often powdery or earthy.  $H. = 4 \pm$ .  $G. = 2.7\text{--}4.3$ .  $F. = 7$ . Soluble in  $\text{HCl}$ . Isotropic with  $N = \text{about } 2.0\text{--}2.1$ . Also with anomalous birefringence up to about 0.04. This is submicroscopically crystalline (goethite). A red isotropic substance has  $N = 2.2\text{--}2.4$  (limonite with very little water?). Limonite in mass is yellow, brown, or brownish black. Streak brownish, yellowish brown (to reddish). Luster vitreous to dull. In section yellow to brownish. Very common as an alteration product of iron minerals; found in all kinds of rocks. Common in the oxide zone of veins, and also as a hot spring deposit, occasionally in sufficient abundance to serve as an iron ore. Common in sediments, forming some important ores. Also forms in swamps as "bog iron ore." Common in submicroscopic particles staining other minerals.

<sup>117</sup> H. Schwierisch: *Chem. Erde*, VIII, 252 (1933).

**Groutite** <sup>117a</sup> ( $HMnO_2$ ) is orthorhombic with  $a:b:c = 0.426:1:0.268$ . Space group  $Pbnm$ ;  $a$  4.58,  $b$  10.76,  $c$  2.89 Å. Crystals wedge-shaped, faces often curved. Perfect 010 and distinct 100 cleavage.  $H. = 3.5$ .  $G. = 4.14$ . Infusible. Indices not measured, but doubtless near those of goethite. Color jet black. Pleochroic with  $b =$  yellowish brown,  $c =$  very dark brown to black. Found on the Cuyuna range in Minnesota.

## 2. Multiple oxides with type formula $AB_2X_4$

### SPINEL GROUP

The spinel group has about a dozen end-member formulas, but only those showing miscibility in all proportions belong to any one mineral. In natural minerals of the spinel group  $Fe'''$  replaces Al or Cr probably only to a limited extent,<sup>118</sup> whereas Al can be replaced by Cr in any proportion.<sup>119</sup> Accordingly, the spinel group includes two minerals: spinel and magnetite.

Spinel	$(Mg, Fe, Zn, Mn)(Al, Cr)_2O_4$
Magnetite	$(Fe, Mg, Mn, Zn, Ni)Fe_2O_4$

Both spinel and magnetite may contain an excess of the trivalent base, causing the existence of some vacant spaces, normally occupied by divalent atoms. The natural mineral consists rather rarely of as much as 50% of one end-member.

### SPINEL ISOMETRIC HEXOCTAHEDRAL $(Mg, Fe, Zn, Mn)(Al, Cr)_2O_4$

**COMP.** There is a continuous series from  $MgAl_2O_4$  (*spinel proper*) to  $FeAl_2O_4$  (*hercynite*) and also from  $MgAl_2O_4$  to  $MgCr_2O_4$  (*picrochromite*) and from that to  $FeCr_2O_4$  (*chromite*). See Fig. 49. Furthermore, there is probably a continuous series from  $MgAl_2O_4$  to  $ZnAl_2O_4$  (*gahnite*) and to  $MnAl_2O_4$  (*galaxite*). *Ceylonite* and *pleonaste* are varieties intermediate between magnesiospinel (= spinel proper) and hercynite; *picotite* contains also some  $FeCr_2O_4$ . *Chlorospinel* is  $MgAl_2O_4$  with some  $FeFe_2O_4$ . Artificial gem spinels may contain as much as 60%  $Al_2O_3$ .

**STRUC.** Space group  $Fd3m$ ;  $a$  8.086 Å for  $MgAl_2O_4$ , 8.119 for  $FeAl_2O_4$ , 8.062 for  $ZnAl_2O_4$ , 8.271 for  $MnAl_2O_4$ , 8.305 for  $MgCr_2O_4$ , 8.344 for  $FeCr_2O_4$ . U.C. 8.

**PHYS. CHAR.** Crystals usually octahedral; often massive, granular. Twinning on 111, sometimes multiple. No cleavage in  $(Fe, Mg)Cr_2O_4$ ;

<sup>117a</sup> J. W. Gruner: *Am. Mineral*, XXXII, 654 (1947); R. L. Collin and W. N. Lipscomb: *Acta Cryst.*, II, 104 (1949).

<sup>118</sup> The evidence of a continuous series from  $FeFe_2'''O_4$  to  $Mg(Al, Cr)_2O_4$  presented by R. E. Stevens (*Am. Mineral.*, XXIX, 1, 1944) is not convincing.

<sup>119</sup> W. T. Wilde and W. J. Rees: *Trans. Brit. Cer. Soc.*, XLII, 123 (1943).



poor cleavage (or parting?) on 111 in  $(\text{Mg,Fe,Zn,Mn})\text{Al}_2\text{O}_4$ .  $H. = 5.5-8$ .  $G. = 3.55-5.09$ , varying with composition as follows (see also

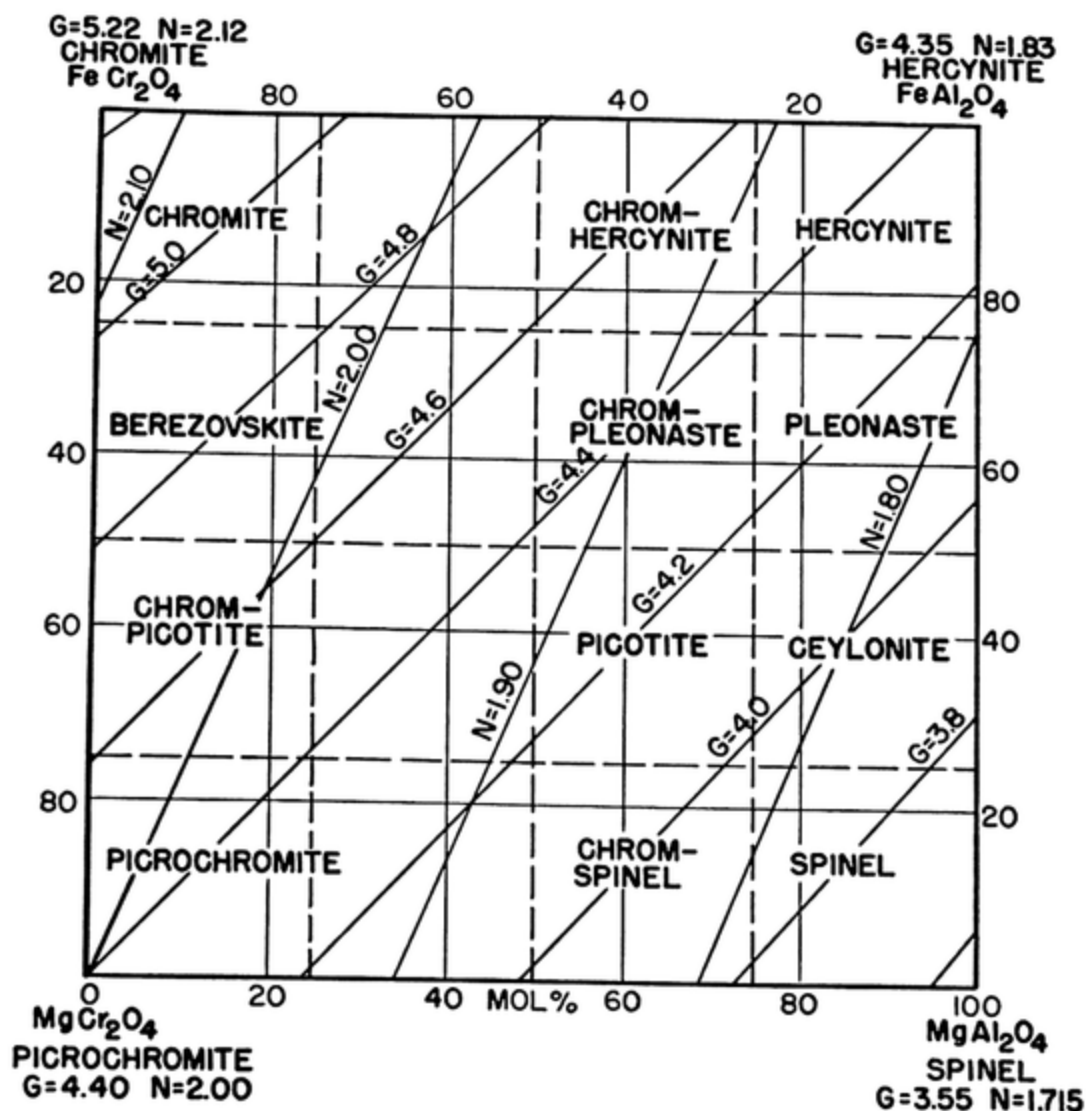


FIG. 49. Properties of spinel  $[(\text{Mg,Fe})(\text{Al,Cr})_2\text{O}_4]$ .

Figs. 49-51).  $F. = 7$  (6 for chromite). Slowly soluble ( $\text{ZnAl}_2\text{O}_4$ ,  $\text{MgAl}_2\text{O}_4$ ) to insoluble in  $\text{H}_2\text{SO}_4$ .

Spinel Proper <sup>120</sup> $\text{MgAl}_2\text{O}_4$	Hercy- nite <sup>121</sup> $\text{FeAl}_2\text{O}_4$	Gahnite $\text{ZnAl}_2\text{O}_4$	Galaxite $\text{MnAl}_2\text{O}_4$	Picro- chromite $\text{MgCr}_2\text{O}_4$	Chromite <sup>121</sup> $\text{FeCr}_2\text{O}_4$
$H. = 8.0$	7.5	7.5	7.5	5.5	5.5
$G. = 3.58$	4.39	4.62	4.03	4.43	5.09
$N = 1.715$	1.83	1.805	1.848 calc.	2.00 calc. 2.054 <sup>122</sup>	2.12

$$N_F - N_C = 0.012$$

$$0.02 \pm$$

<sup>120</sup> B. W. Anderson and C. J. Payne: *Mineral. Mag.*, XXIV, 547 (1937).

<sup>121</sup> W. Hugill: *Iron and Steel Inst. (London), Special Rept.*, 26, 201 (1939).

<sup>122</sup> R. Bailly: *Am. Mineral.*, XXXIII, 528 (1948).

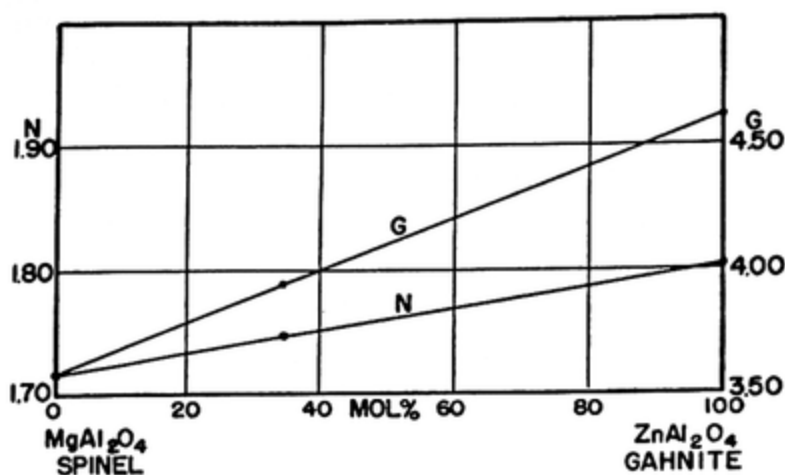
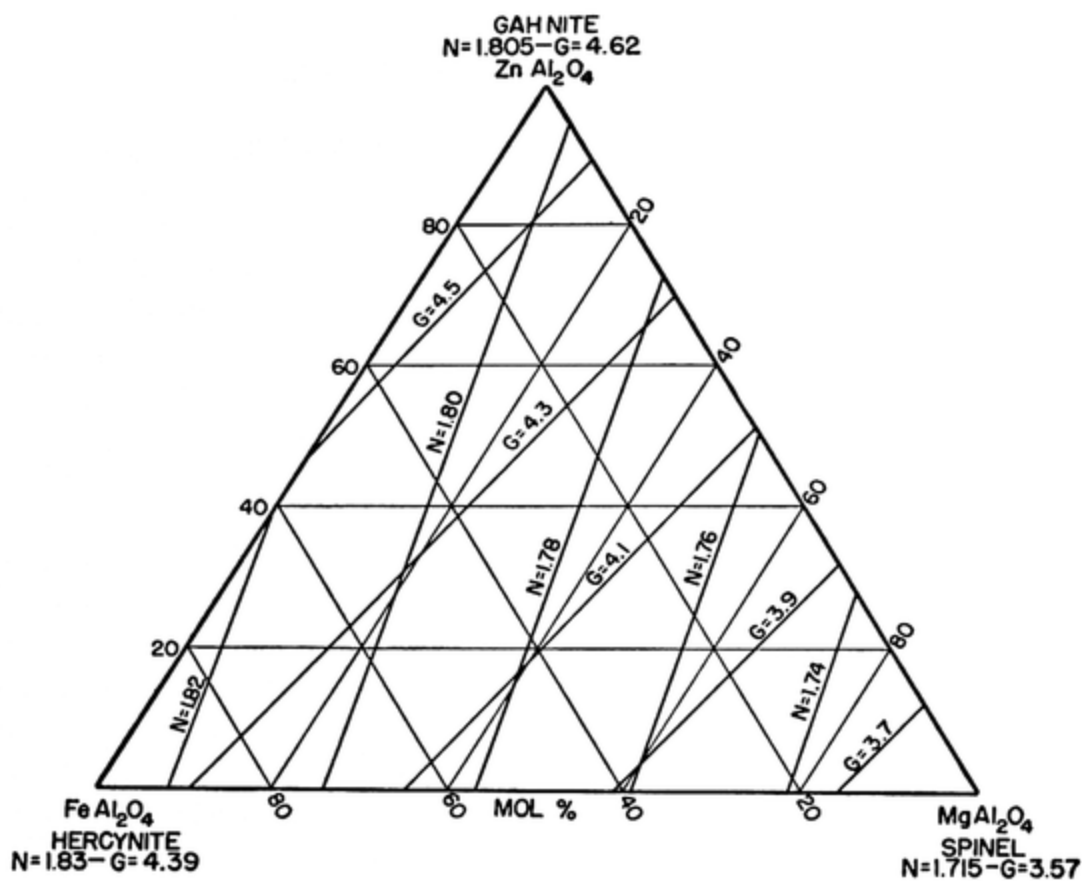


FIG. 50. Properties of the spinel-gahnite series.



SPINEL-HERCYNITE-GAHNITE

FIG. 51. Properties of the spinel-gahnite-hercynite system.

OPT. PROP. Isotropic with high refringence,  $N = 1.719\text{--}2.12$ , varying with composition as given above. See also Figs. 49–51. The properties of the  $\text{MgAl}_2\text{O}_4\text{--Al}_2\text{O}_3$  series are shown in Fig. 52.

Color of spinel proper is red, blue,<sup>123</sup> green, yellow, brown, black, or, rarely, nearly white. Color of hercynite black (green in thin section). Color of gahnite green, black, blue (rarely brown, when  $\text{Fe}_2\text{O}_3$  is present, as in *dysluite*). Color of galaxite brown to black; color of picrochromite and chromite black (black to brown or red in thin section). Color of *ceylonite* and *pleonaste* (see Fig. 49) green to brown (with  $\text{Fe}_2\text{O}_3$ ). Color

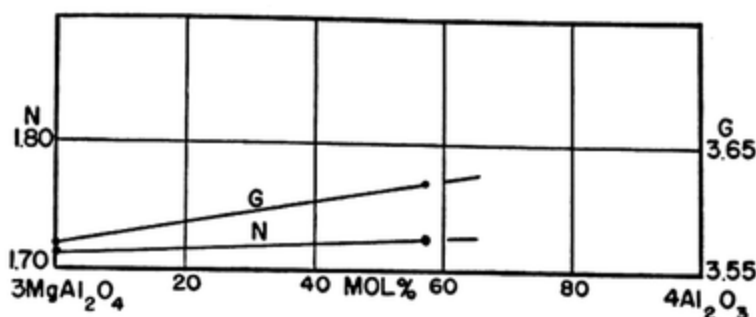


FIG. 52. Properties of the  $\text{MgAl}_2\text{O}_4\text{--Al}_2\text{O}_3$  partial series.

of *picotite* (see Fig. 49) yellowish or greenish brown. Streak lighter in all cases.

In polished section chromite is isotropic and gray-white with a brownish tint; reflection percentages:<sup>3</sup> red and orange 12.5, green 15.

Gem varieties of spinel include: *ruby-spinel* (rose-red), *rubicelle* (yellow or orange-red), *almandine-spinel* (violet), *ceylonite* (green or blue), *pleonaste* (green or blue), *gahnospinel* (blue), *picotite* (yellowish to greenish brown), *chlorospinel* (grass green).

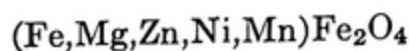
ALTER. Usually unaltered even in much-decayed rocks, but it may alter to serpentine or talc.

OCCUR. Spinel proper is a high-temperature mineral; it is found especially in contact-metamorphosed limestones and schists; also as an accessory in igneous rocks, especially basic types; rare in veins; chromite is derived chiefly from basic igneous rocks and serpentines; also in placer deposits; also in meteorites. Hercynite is found in contact rocks rich in alumina. Chromite occurs in basic igneous rocks, serpentine, and even in schists and dolomite. Gahnite is found in pegmatites, veins, and schists.

DIAG. Spinel differs from garnet by its octahedral form (rare in garnet) and by the absence of silica; chromite has much less magnetism than magnetite; it has greater density and darker color than picotite or hercynite.

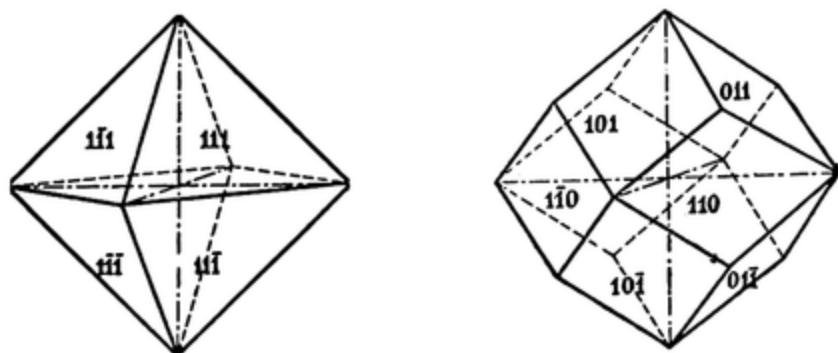
<sup>123</sup> At least in some cases the blue color is due to presence of Co; in other cases (*gahnospinel*), due to Fe. See B. W. Anderson: *Mineral. Mag.*, XXIV, 547.

## MAGNETITE



## ISOMETRIC HEXOCTAHEDRAL

COMP. The natural mineral may be (nearly) pure  $FeFe_2O_4$ , and there seems to be continuous variation from this end-member to  $MgFe_2O_4$  and to  $MnFe_2O_4$ , and also from the last named to  $ZnFe_2O_4$  and probably to  $MgFe_2O_4$ . Ni is very rare, but a continuous series with  $Fe''$  is prob-



FIGS. 53, 54. Crystal forms of magnetite.

ably possible. Even Pb may replace  $Fe''$ , at least in part, as in *plumboferrite*. Also,  $Fe'''$  may be replaced in minor amount by Al, Cr, or even  $Mn'''$ , or V, or Ti as in *titanomagnetite*. Finally  $Fe_3O_4$  may be changed artificially, in whole or in part, to  $Fe_2O_3$  (*oxymagnite*),<sup>124</sup> and samples from such a series are known in nature. *Martite* is  $Fe_2O_3$  pseudomorphous after magnetite (or pyrite).

STRUC. Space group <sup>22</sup>  $Fd3m$ ;  $a$  8.31 Å for  $Fe_2O_3$ , 8.366 for  $MgFe_2O_4$ , 8.374 for  $FeFe_2O_4$ , 8.403 for  $ZnFe_2O_4$ , 8.41 for  $NiFe_2O_4$ , and 8.457 for  $MnFe_2O_4$ . U.C. 8 ( $Fe_2O_3$  cell is  $Fe_{21\frac{1}{2}}O_{32}$ ).

PHYS. CHAR. Crystals commonly octahedral; also dodecahedral; cubes rare. See Figs. 53, 54. Also massive, laminated, or granular. Twinning on 111, sometimes lamellar. Octahedral parting may be well developed. H. = 5.5–6.5 (5 for  $NiFe_2O_4$ ). G. = 4.5–5.3, varying with the composition as follows (see also Fig. 55):

	Magnesio- ferrite $MgFe_2O_4$ <sup>125</sup>	Magnetite (proper) $FeFe_2O_4$	Frank- linite $ZnFe_2O_4$	Jacob- site $MnFe_2O_4$	Tre- vorite $NiFe_2O_4$	Oxy- magnite $Fe_2O_3$
H. =	6–6.5	5.5–6.5	5.5	5.5	5	5
M.P. =	1580–1610°	1591°	F. = 7	F. = 7	?	?
G. =	4.5	5.20	5.32	5.03	5.16	4.74 calc.
N =	2.38 ca.	2.42 Na	2.36 ca. Li	2.3 ca. Li	2.3	2.52–2.74 Li

<sup>124</sup> Called *maghemite* in *Dana's Syst. Mineral.*, 7th Ed., I, 708 (1944).

<sup>125</sup> W. Hugill: *Min. Abst.*, IX, 13 (1944), gives G. = 4.20 for artificial  $MgFe_2O_4$ .

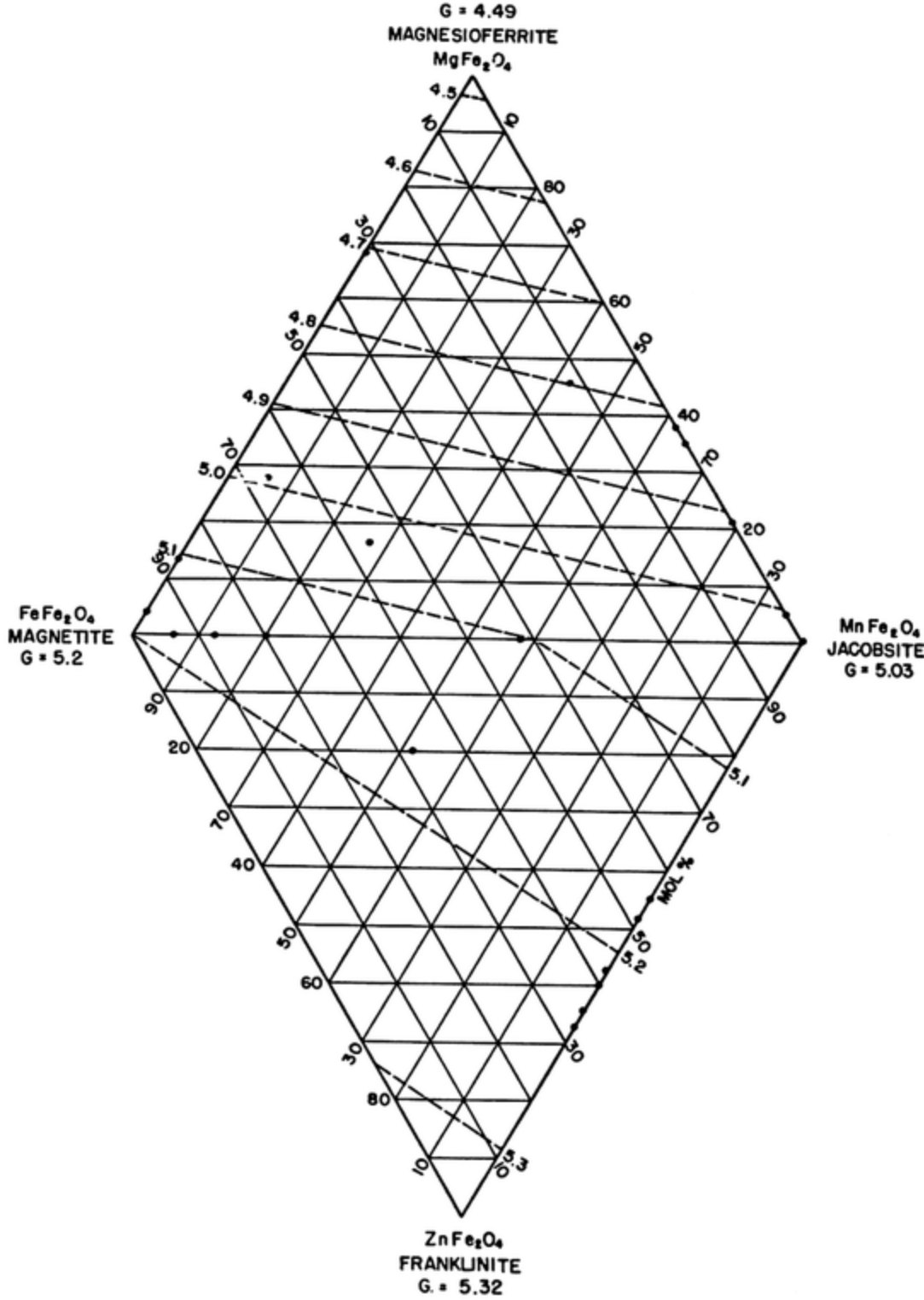


FIG. 55. Specific gravity of magnetite.

Magnetic:  $MgFe_2O_4$ ,  $FeFe_2O_4$ , and  $NiFe_2O_4$  strongly so;  $MnFe_2O_4$  and  $ZnFe_2O_4$  weakly magnetic. Some  $FeFe_2O_4$  has polarity (*lodestone*). Soluble in HCl.

OPT. PROP. Opaque, or nearly so; very thin splinters may transmit a little light. Isotropic with  $N = 2.3-2.42$ , as given above. Color black (to brownish black); oxymagnite is brown. Streak black (magnetite and magnesioferrite) to reddish brown (franklinite) and brown (jacobsonite, trevorite, and oxymagnite). Color in transmitted light dark reddish brown, except oxymagnite which is brown to yellow. In polished section, isotropic with:

	Color	Internal Reflection	Reflection Percentages <sup>3</sup>		
			Red	Orange	Green
Magnetite (proper)	Gray (brownish)	None	21	21	21
Franklinite	White	Red	14	14.5	16.5
Jacobsonite	Gray-white (olive)	Brown	16	17	19.5
Oxymagnite	White to grayish blue	?			

In thin section magnetite ( $FeFe_2O_4$ ) has a steel blue color in oblique reflected light.

ALTER. Magnetite proper alters to hematite, limonite, or oxymagnite, etc.; it may be produced by alteration of hematite, siderite, pyrite, amphibole, etc. It may be changed to oxymagnite by heating in oxygen to  $220^\circ C.$ ; it then inverts to hematite at about  $530^\circ C.$

INCL. Apatite and zircon occur as inclusions in magnetite ( $FeFe_2O_4$ ) in some igneous rocks. By dissolving the enclosing magnetite, ilmenite has been found within, so oriented that the trigonal axes of the two minerals are parallel. Occasionally, rutile needles have been found lying parallel with the octahedral edges.

OCCUR. Magnetite ( $FeFe_2O_4$ ) is very widespread in its occurrence in igneous and metamorphic rocks. It is found sparingly in acid rocks, but more abundantly in some basic types, even forming important masses of iron ore in rare cases. Similar masses may be formed by metamorphism of deposits of limonite or hematite. It is one of the earliest minerals to solidify from magmas, associated in time with apatite and zircon, and often enclosed in the ferromagnesian silicates. Recrystallization of augite at high temperature may result in paramorphs of hornblende and biotite with borders of magnetite; cleavage lines of the formerly existing pyroxene may be marked also by magnetite.

Franklinite is an important zinc ore at Franklin, New Jersey, where

it is often associated with calcite, zinkite, willemite, rhodonite, and tephroite.

Magnesioferrite is rare; it is found with hematite about volcanoes.

Jacobsite is found in limestone at Jacobsberg, Sweden.

Trevorite is found in talc in South Africa.

Oxymagnite probably forms by slow oxidation of magnetite; rare.

DIAG. Magnetite ( $\text{FeFe}_2\text{O}_4$ ) is distinguished from hematite and chromite in thin section by its blue-black color in reflected light. It is distinguished from graphite by its crystal form, hardness, and usually better metallic luster. It is distinguished from ilmenite by its crystal form, strong magnetism, and ready solubility in HCl. Ilmenite alters to leucoxene, but this may also develop from titaniferous magnetite.

Magnesioferrite, if opaque, may be distinguished from magnetite only by chemical tests for magnesium.

Franklinite differs from magnetite by its associated minerals, dark reddish brown streak, weaker magnetism, and chemical tests for Zn and Mn.

Oxymagnite differs from magnetite in color and streak.

**MINIUM** <sup>126</sup>                      TETRAGONAL(?)       $c/a = 0.745$                        $\text{PbPb}_2\text{O}_4$

STRUC.<sup>127</sup> Space group  $P4/mbc$ ;  $a$  8.80,  $c$  6.56 Å. U.C. 4.

PHYS. CHAR. Found only as a fine powder. H. = 2.5. G. = 8.9–9.2 (artificial). F. = 1.5.

OPT. PROP. Refrindex extreme with weak birefringence; parallel extinction and negative elongation. Abnormal green interference colors are characteristic.  $N = 2.42$  Li. Color vivid red with X = reddish brown, Z = nearly colorless. Streak orange-yellow. Optic sign unknown.

OCCUR. An alteration product of galena or cerussite, as at Badenweiler, Germany; Leadville, Colorado; etc.

**HAUSMANNITE**      DITETRAGONAL DIPYRAMIDAL       $c/a = 1.636$        $\text{MnMn}_2\text{O}_4$

STRUC. Space group <sup>128</sup>  $I4/amd$ ;  $a$  5.75,  $c$  9.42 Å. U.C. 4.

PHYS. CHAR. Crystals pyramidal with distinct basal cleavage. Twinning on 101. H. = 5.5. G. = 4.84. F. = 7. Soluble in HCl.

OPT. PROP. Uniaxial negative with  $N_O = 2.46$  Li,  $N_E = 2.15$ ,  $N_O - N_E = 0.31$ . Color brownish black; streak chestnut brown. In very thin section deep reddish brown and not pleochroic. In polished section <sup>3</sup> grayish white and weakly pleochroic with  $O < E$ ; reflection percentages; red 13, orange 16.5, green 20.

OCCUR. Found in veins, contact deposits, and as a product of weathering. Known at Jacobsberg, Sweden; Batesville, Arkansas; etc.

<sup>126</sup> Minium, like magnetite and hausmannite, is chemically a simple oxide; it is a multiple oxide in that it has metallic atoms of two sizes, not closely similar.

<sup>127</sup> A. Byström and A. Westgren: *Min. Abst.*, IX, 43 (1944).

<sup>128</sup> G. Aminoff: *Zeit. Krist.*, LXIV, 475 (1926).



**Heterolite** ( $\text{ZnMn}_2\text{O}_4$ ) is ditetragonal dipyramidal<sup>129</sup> with  $c/a = 1.595$ ; space group<sup>129</sup>  $I4/amd$ ;  $a$  5.74,  $c$  9.15 Å. U.C. 4. Fibrous with 001 cleavage.  $H. = 6$ .  $G. = 5.18$ .  $F. = 7$ . Soluble in HCl. Uniaxial negative with  $N_O = 2.35$ ,  $N_E = 2.10$ ,  $N_O - N_E = 0.25$ . Color dark brown to black. Streak dark brown. Red-brown in section with  $O < E$ , faint. Found at Sterling Hill, New Jersey, etc. A sample called *hydroheterolite*<sup>129</sup> ( $\text{Zn}_2\text{Mn}_4\text{O}_8 \cdot \text{H}_2\text{O}?$ ) from Leadville has  $G. = 4.65$ ,  $N_O = 2.26$ ,  $N_E = 2.10$ ,  $N_O - N_E = 0.16$ . Fibers are elongated normal to {110} and have positive elongation and parallel extinction.

**Nigerite**<sup>130</sup>  $[(\text{Zn}, \text{Fe}, \text{Mg})(\text{Sn}, \text{Zn})_2(\text{Al}, \text{Fe})_{12}\text{O}_{22}(\text{OH})_2]$  is hexagonal with  $c/a = 2.423$ .  $a$  5.71,  $c$  13.83 kX. Crystals show {0001} and poor trigonal pyramid faces.  $H. = 8.5$ .  $G. = 4.5$ . Uniaxial positive with  $N_O = 1.80$ ,  $N_E = 1.81$ ,  $N_E - N_O = 0.01$ . Color brown. Found in quartz-sillimanite rocks, Kabba Province, central Nigeria.

**CHRYSOBERYL**

## ORTHORHOMBIC DIPYRAMIDAL



$$a:b:c = 0.582:1:0.471$$

**COMP.** Often contains Fe (to 6%  $\text{Fe}_2\text{O}_3$ ) replacing Al? Also less Cr.

**STRUC.** Space group<sup>131</sup>  $Pmn$ ;  $a$  5.47,  $b$  9.39,  $c$  4.42 Å. U.C. 4.

**PHYS. CHAR.** Crystals often {001} tablets. Twinning on 130, simple, or cyclic giving pseudo-hexagonal forms. Distinct 110 cleavage.  $H. = 8.5$ .  $G. = 3.7$ .  $F. = 7$ . Insoluble.

**OPT. PROP.** The optic plane is 010;  $X = c$ . See Fig. 56. Heat causes the optic axes to come together and then separate in the 100 plane. Optic angle and indices very variable even in a single crystal (due to Fe content?)  $(+ )2V = 10^\circ, 45^\circ, 67^\circ, 71^\circ$ ,  $r < v$ ,  $N_X = 1.744-1.747$ ,  $N_Y = 1.747-1.749$ ,  $N_Z = 1.753-1.758$  Na,  $N_Z - N_X = 0.009 \pm$ ,  $N_{T1} - N_{L1} = 0.008 \pm$ .  $N_Z - N_X$  on 110 cleavage = 0.0035.

Color green of various shades, yellow, brown, red. Colorless in thin section. Pleochroic in thick sections with  $X =$  columbine red,  $Y =$  orange-yellow,  $Z =$  emerald green. *Alexandrite* is a gem variety which is emerald green to gray in sunlight, but columbine red by artificial light.

**OCCUR.** Found in pegmatite in New England, etc.; also in micaceous schists in the Urals; also in alluvial deposits in Brazil and Ceylon.

**DIAG.** Very high relief with weak birefringence; very hard, and high in density; infusible and insoluble.

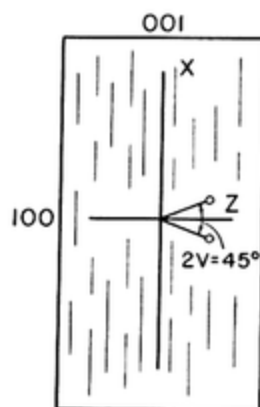
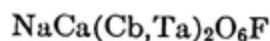


FIG. 56. The optic orientation of chrysoberyl.

### 3. Multiple oxides with type formula $A_mB_nX_p$ and $(m + n):p \approx 2:3$

**PYROCHLORE**

## ISOMETRIC HEXOCTAHEDRAL



**COMP.** Besides a complete series from Cb to Ta, some Ti, and probably Si, Sn, Fe''', and W may be present in place of Cb, and K, Mg, Fe'', Mn'', Ce, Y, U<sup>4</sup>, U<sup>6</sup>,

<sup>129</sup> C. Frondel and E. W. Heinrich: *Am. Mineral.*, XXVII, 48 (1942).

<sup>130</sup> F. A. Bannister, M. H. Hey, and H. P. Stadler: *Mineral. Mag.*, XXVIII, 129 (1947).

<sup>131</sup> W. L. Bragg and G. B. Brown: *Zeit. Krist.*, LXIII, 122 (1926).

Th, and Zr may apparently proxy for NaCa. The Cb end-member has been named *columbomicrolite*; <sup>132</sup> the Ta end-member is *microlite*; *hatchettolite* contains U and Ti; *chalcolamprite* contains Si (due to admixture?); *koppite* contains Ce and Fe'''; *marignacite* contains Y, Ce, Si, H; *neotantalite* contains Fe, Mn, H; *ellsworthite* contains U<sup>4</sup>, U<sup>6</sup>, Fe''', Ti, H; *pyrrhite* contains Ti, etc.

STRUC. Space group <sup>133</sup> *Fd3m*. *a* 10.37 Å (pyrochlore); 10.4 (microlite). U.C. 8.

PHYS. CHAR. Crystals octahedral; 111 twinning; poor 111 cleavage. *H.* = 5–5.5. *G.* = 4.16–6.4 increasing with Ta content; hydration causes a marked decrease of density. *F.* = 7. Decomposed by H<sub>2</sub>SO<sub>4</sub>.

OPT. PROP. Isotropic usually, but may show weak birefringence. *N* = 1.93–2.18. Index decreases with hydration; increases on ignition, even to 2.27. *Columbomicrolite* has *N* = 2.152; *microlite* has *N* = 1.93; *koppite* has *N* = 2.12–2.18; *pyrrhite* has *N* = 2.16; *hatchettolite* has *N* = 1.98 *ca.*; *neotantalite* has *N* = 1.95–1.99; *chalcolamprite* has *N* = 1.87 *ca.*; *ellsworthite* has *N* = 1.89 *ca.*

Color in mass brown to black (*columbomicrolite*); yellow to brown, red, olive, green (*microlite*). Streak brown to yellow. In section brown, red, yellow, or colorless. May show zonal arrangement of color.

OCCUR. Found in pegmatites with zircon, apatite, etc. Also in alluvial deposits. Widely, but very sparingly, distributed, as at Laurvik, Norway; Schelingen, Baden; Haddam, Connecticut; etc.

**Zirkelite** [(Ca,Fe,Th,U)<sub>2</sub>(Ti,Zr)<sub>2</sub>O<sub>6</sub>] is isometric in flattened octahedrons. *H.* = 5.5. *G.* = 4.74. Isotropic with *N* = 2.19. Color black in mass; dark brown in thin splinters. Found in Brazil with perovskite.

**Schafarzikite** <sup>134</sup> (5FeO·2Sb<sub>2</sub>O<sub>3</sub>) is ditetragonal dipyramidal with *c/a* = 0.954. Crystals prismatic with perfect 110 and distinct 100 cleavages. *H.* = 3.5. *G.* = 4.3. Uniaxial positive with *N* much above 1.74, *N<sub>E</sub>* – *N<sub>O</sub>* = weak. Color red with *O* = straw yellow, *E* = brownish yellow. Found in antimony ore in Hungary.

**Wiserite** <sup>135</sup> (2MnO·3Mn<sub>2</sub>O<sub>3</sub>·CO<sub>2</sub>·8H<sub>2</sub>O?) is uniaxial with *N<sub>O</sub>* = 1.74, *N<sub>E</sub>* = 1.66–1.67, *N<sub>O</sub>* – *N<sub>E</sub>* = 0.07–0.08. Fibers reddish to brown. *E* pale orange yellow, *O* colorless. Found in veins in manganese ore.

**Hematophanite** [Pb<sub>5</sub>Fe<sub>4</sub>O<sub>10</sub>(Cl,OH)<sub>2</sub>] is ditetragonal dipyramidal <sup>136</sup> with *c/a* = 1.95. *a* 7.80, *c* 15.23 Å. U.C. 4. Good 001 cleavage. *H.* = 2–3. *G.* = 7.70. Uniaxial negative with weak birefringence. Color blood red in section, red-brown in mass. Luster submetallic. Found in ore at Jacobsberg, Sweden.

**Hoegbomite** [Mg(Al,Fe,Ti)<sub>4</sub>O<sub>7</sub>?] is hexagonal with <sup>66</sup> *c/a* = 3.11. Poor 0001 cleavage. *H.* = 6.5. *G.* = 3.8. Uniaxial negative with *N<sub>O</sub>* = 1.853, *N<sub>E</sub>* = 1.803, *N<sub>O</sub>* – *N<sub>E</sub>* = 0.050. Again: <sup>137</sup> *N<sub>O</sub>* = 1.848, *N<sub>E</sub>* = 1.817, *N<sub>O</sub>* – *N<sub>E</sub>* = 0.031. Color black in mass with metallic luster; in section, brown with *O* = dark golden brown, *E* = light golden brown. Found in iron ore in Lapland, at Peekskill, New York, etc.

**Chalcophanite** [(Zn,Mn,Fe)Mn<sub>2</sub>O<sub>5</sub>·2H<sub>2</sub>O?] is hexagonal with *c/a* = 3.527. Perfect 0001 cleavage. *H.* = 2.5. *G.* = 4.0. Color in mass bluish to iron black; in section, *O* = nearly opaque, *E* = deep red. Uniaxial negative with *N<sub>O</sub>* much above

<sup>132</sup> J. E. de Villiers: *Am. Mineral.*, XXVI, 501 (1941).

<sup>133</sup> H. R. Gaertner: *Jahrb. Min.*, Bl. Bd. LXI, 1 (1930).

<sup>134</sup> L. Tokody: *Zeit. Krist.*, LXII, 123 (1925); H. Hueber (*Cent. Min.*, 1932A, 337) determined the composition.

<sup>135</sup> W. Epprecht: *Beit. Geol. Schw. Geotech. Ser.*, 1946, No. 24; *Schw. Min. Pet. Mtl.*, XXVI, 19 (1946).

<sup>136</sup> K. Johansson: *Zeit. Krist.*, LXVIII, 87 (1928); *Min. Abst.*, IV, 13 (1929).

<sup>137</sup> C. S. Ross in T. L. Watson: *Am. Mineral.*, X, 1 (1925).

2.72,  $N_E$  near 2.72,  $N_O - N_E = \text{strong}$ . An alteration product at Franklin, New Jersey.

**Swedenborgite**<sup>138</sup> ( $\text{NaBe}_4\text{SbO}_7$ ) is dihexagonal pyramidal with  $a:c = 1:1.631$ . Space group  $C6mc$ ;  $a$  5.47,  $c$  8.92 Å. U.C. 2. Crystals short prisms with distinct basal cleavage.  $H. = 8$ .  $G. = 4.29$ . Insoluble. Uniaxial negative with  $N_O = 1.7724$ ,  $N_E = 1.7700$ ,  $N_O - N_E = 0.0024$ ;  $F - C$  for  $N_O = 0.0128$ . Colorless to yellow. Found in ores at Långban, Sweden.

**Derbylite**<sup>139</sup> ( $6\text{FeO} \cdot 5\text{TiO}_2 \cdot \text{Sb}_2\text{O}_5?$ ) is orthorhombic dipyramidal with  $a:b:c = 0.966:1:0.550$ . Crystals prismatic; cruciform twinning common.  $H. = 5$ .  $G. = 4.52$ .  $F. = 7$ . Insoluble in acid.  $(+)2V = \text{nearly } 0^\circ$ .  $N_X = 2.45$ ,  $N_Y = 2.45$ ,  $N_Z = 2.51$ ,  $N_Z - N_X = 0.06$ .<sup>66</sup> Color black; in section dark brown and not pleochroic. Found in placers of Tres Cruces, Minas Geraes, Brazil.

# **PSEUDOBROOKITE**

ORTHORHOMBIC DIPYRAMIDAL

$\text{Fe}_2\text{TiO}_5$

$a:b:c = 0.986:1:0.375$

STRUC. Space group <sup>140</sup>  $Cmcm$ ;  $a$  9.79,  $b$  9.93,  $c$  3.725 Å. U.C. 4.

PHYS. CHAR. Crystals {100} tablets with distinct 010 cleavage.  $H. = 6$ .  $G. = 4.4$ .  $F. = 7$ . Decomposed by  $\text{H}_2\text{SO}_4$ .

OPT. PROP. The optic plane is 001;  $X = b$ .  $(+)2V = 50^\circ$ ,  $r < v$ .  $N_X = 2.38$ ,  $N_Y = 2.39$ ,  $N_Z = 2.42$ ,  $N_Z - N_X = 0.04$  (Larsen); again <sup>141</sup>  $N_X = 2.345\text{--}2.350$ ,  $N_Z$  near 2.375; and <sup>142</sup>  $N_X = 2.42$ ,  $N_Z = 2.47$ . See Fig. 57. Color in mass dark brown to black; in section reddish brown with  $X < Y > Z$ .

OCCUR. Found in cavities in igneous rocks, as at Vesuvius, at Crater Lake, Oregon, etc.

DIAG. Differs from brookite in form, larger optic angle, and absence of marked dispersion.

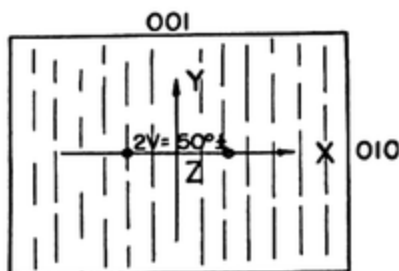


FIG. 57. The optic orientation of pseudobrookite.

# **PEROVSKITE**

PSEUDO-ISOMETRIC <sup>143</sup> (MONOCLINIC?)

$\text{CaTiO}_3$

COMP. Cb may proxy for Ti up to  $\text{Cb:Ti} = 2:5$  (*dysanalyte*); Ce (and other rare earths) may proxy for Ca up to  $\text{Ce:Ca} = 4:7$  (or more?) (*knopite*); with both Ce and Cb it is called *loparite* (also *metaloparite*); Fe and (Na,K) may be present.

STRUC. Space group <sup>144</sup>  $P2_1/m$ ;  $a, b, c$  all  $\approx 7.60$  Å,  $\beta \approx 90^\circ$ ;  $a$  for pseudo-isometric unit cell is 7.59–7.65 Å in  $\text{CaTiO}_3$  and 7.65–7.71 in  $\text{Ca}(\text{Ti,Cb})\text{O}_3$ . U.C. 8.

<sup>138</sup> G. Aminoff: *K. Svensk. Vet. Akad. Hand.*, XI, No. 4, 3 (1933). Also: L. Pauling, H. P. Klug, and A. N. Winchell: *Am. Mineral.*, XX, 492 (1935).

<sup>139</sup> E. Hussak and G. T. Prior: *Mineral. Mag.*, XI, 85, 176 (1897).

<sup>140</sup> L. Pauling: *Zeit. Krist.*, LXXIII, 97 (1930).

<sup>141</sup> P. Ramdohr: *N. Jahrb. Min.*, I, 248 (1926).

<sup>142</sup> A. S. Starrabba: *Min. Abst.*, IX, 156 (1943).

<sup>143</sup> O. Zedlitz: *N. Jahrb. Min.*, Bl. Bd. LXXV, 245 (1939).

<sup>144</sup> O. Zedlitz: *Naturwiss.*, XXXI, 369 (1943). Also described as orthorhombic with  $a$  10.74,  $b$  7.63,  $c$  10.86 Å by H. D. Megaw in *Proc. Phys. Soc. London*, LVIII, 133 (1946).

**PHYS. CHAR.** Crystals cubic or octahedral with poor cubic cleavage. Intimate penetration twinning on 111 common.  $H. = 5.5$ .  $G. = 4.0$  ( $\text{CaTiO}_3$ ), 4.1–4.9 for  $(\text{Ca,Ce})(\text{Ti,Cb})\text{O}_3$ .  $F. = 7$ . Decomposed by  $\text{H}_2\text{SO}_4$ .

**OPT. PROP.** Small crystals usually isotropic with  $N = 2.38 \pm$ . Large crystals anisotropic with complex twinning, like that of garnet or boracite, of monoclinic units with  $Y = b$  and  $Z \wedge c$  (or  $a$ ) =  $45^\circ$ .  $(+)2V =$  about  $90^\circ$ , with  $r > v$  about  $Z$ .

			With Ce, Fe <sup>22</sup>	With Ce <sup>22</sup>	With Ce, H <sup>146</sup>	With Cb <sup>22</sup> Dys- analyte
	$\text{CaTiO}_3$ <sup>145</sup> Iron Hill, Colorado	$\text{CaTiO}_3$ <sup>66</sup> ?	Knopite Kola Peninsula	Knopite Alnö, Sweden	Metaloparite Lovozero	Magnet Cove, Arkansas
$N = 2.34$		2.38	2.37	2.30	2.24	2.33
$N_Z - N_X = 0.002$		Weak	?	?	?	0.00
$G = ?$		4.03	?	?	4.41	4.18

Color black, brown, yellow; in thin section gray, brownish, rarely greenish; the color may be in zones. Weakly pleochroic with  $X < Z$ .

**OCCUR.** Found as a rare accessory mineral in basic igneous rocks; also in some contact rocks and schists. It may form by alteration of ilmenite. Localities include Vesuvius, Italy; Alnö, Sweden; Magnet Cove, Arkansas; Syracuse, New York; etc.

**DIAG.** The extreme refringence, complex twinning (in large crystals), color, and weak birefringence are characteristic.

**Manganostibite**  $[8\text{MnO} \cdot (\text{Sb,As})_2\text{O}_3?]$  is monoclinic and fibrous. Perfect 010 cleavage.  $F. = 7$ . Soluble in  $\text{HCl}$ .  $X = b$ ;  $Z \wedge c =$  large.  $(-)2V =$  small.  $N_X = 1.92$ ,  $N_Y = 1.95$ ,  $N_Z = 1.96$ ,  $N_Z - N_X = 0.04$ . Color black, with  $X =$  reddish brown,  $Y$  and  $Z =$  nearly opaque. Found in a mine at Nordmark, Sweden.

**Uraconite**  $(\text{V}_2\text{O}_4 \cdot n\text{SO}_3 \cdot m\text{H}_2\text{O}?)$  is orthorhombic in laths parallel to  $c$ . Soft. Soluble in acid. The optic plane is 010;  $X = a$ .  $(+)2V =$  medium,<sup>147</sup>  $r < v$  strong.  $N_X = 1.75$ ,  $N_Y = 1.79$ ,  $N_Z = 1.85$ ,  $N_Z - N_X = 0.10$ . Color lemon yellow. Found in Gilpin County, Colorado.

**Minasragrite**  $(\text{V}_2\text{O}_4 \cdot 3\text{SO}_3 \cdot 16\text{H}_2\text{O})$  is monoclinic(?); crystals fibrous or platy with perfect 010 and 110 cleavages with a prism angle of  $78^\circ$ .  $F. =$  easy. Soluble in water. The optic plane<sup>66</sup> is normal to 010;  $Z \wedge$  elongation =  $12^\circ$ .  $(-)2V =$  large.  $N_X = 1.518$ ,  $N_Y = 1.530$ ,  $N_Z = 1.542$ ,  $N_Z - N_X = 0.024$ . Color blue with  $X =$  deep blue,  $Y =$  pale blue,  $Z =$  nearly colorless. An efflorescence on patronite at Minasragra, Peru.

**Quenselite**  $[\text{PbMnO}_2(\text{OH})]$  is monoclinic sphenoidal<sup>148</sup> with  $a:b:c = 1.606:1:0.987$ ,  $\beta = 93^\circ 29'$ . Space group  $P2_1$ ;  $a$  9.12,  $b$  5.68,  $c$  5.60 Å. U.C. 4. Crystals {010} tablets with perfect 001 cleavage.  $H. = 2.5$ .  $G. = 6.84$ .  $F. = 7$ . Optic plane and  $X$  normal to 010;  $Y$  near  $c$ .  $(+?)2V = ?$   $N_X = 2.30$  ca. Color pitch black; streak brown-gray; deep brown in section. Absorption  $X < Z$ . Found at Långban, Sweden.

<sup>145</sup> E. S. Larsen and J. F. Hunter: *J. Wash. Acad. Sci.*, IV, 473 (1914). No analysis.

<sup>146</sup> V. I. Gerasimovsky: *Min. Abst.*, VIII, 341 (1943).

<sup>147</sup> E. S. Larsen: *U. S. Geol. Surv. Bull.* 679 (1921). Uraconite and minasragrite are perhaps sulfates rather than multiple oxides.

<sup>148</sup> A. Byström: *Min. Abst.*, IX, 228 (1946).

**SAPPHIRINE** <sup>22</sup>

MONOCLINIC PRISMATIC



$$a:b:c = 0.69:1:0.70 \quad \beta = 111^\circ 27'$$

COMP. Fe'' may proxy for Mg to at least Mg:Fe = 3:1; AlAl may proxy for MgSi to some extent.

STRUC.  $a$  9.70,  $b$  14.55,  $c$  10.05 Å. U.C. 1.

PHYS. CHAR. Crystal {010} tablets with rare prism faces. No good cleavage.  $H. = 7.5$ .  $G. = 3.4\text{--}3.5$ .  $F. = 7$ . Insoluble in acids.

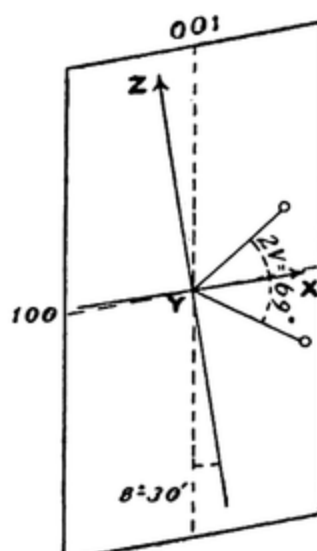


FIG. 58. The optic orientation of sapphirine.

OPT. PROP. The optic plane is 010;  $Z \wedge c = -6^\circ$  (Mountain <sup>149</sup>);  $-8.5^\circ$  (Ussing <sup>150</sup>). See Fig. 58.  $(-)2V = 50^\circ 30'$ ;  $r < v$ , with distinct inclined dispersion.

Locality	Fisker-naes <sup>150</sup>	Transvaal <sup>149</sup>	Quebec <sup>151</sup>
FeO =	0.65	3.09	9.08
2V =	68° 49'	50° 30'	Rather large
N <sub>X</sub> =	1.7055	1.714	1.729 Na
N <sub>Y</sub> =	1.7088	1.719	?
N <sub>Z</sub> =	1.7112 red	1.720 Na	1.734 calc.
N <sub>Z</sub> - N <sub>X</sub> =	0.0057	0.006	0.005
G =	3.486	3.398	3.54
X =	Greenish blue	Pinkish buff	Pale smoky brown
Y =	Dark blue-green	Cerulean blue	Deep sapphire blue
Z =	Yellowish green	Italian blue	?

Color pale blue or green or gray. Pleochroism weak in thin section, but strong in thick plates, as given in the tabulation. Absorption  $X < Y < Z$ .

OCCUR. A high-temperature metamorphic mineral found in schists and gneisses, often with spinel, sillimanite, corundum, cordierite, etc., as at Peekskill, New York.

<sup>149</sup> E. D. Mountain: *Mineral. Mag.*, XXV, 277 (1939).

<sup>150</sup> N. V. Ussing: *Zeit. Kryst.*, XV, 598 (1889).

<sup>151</sup> C. H. Warren: *Am. Jour. Sci.*, CLXXXIII, 263 (1912).

**DIAG.** Differs from corundum by its biaxial character, from lazulite by its weak birefringence, from kyanite, clintonite, and blue amphiboles by its lack of cleavage, and from colored cordierite by its higher refringence and density.

**Arizonite** ( $\text{Fe}_2\text{Ti}_3\text{O}_9$ ) is monoclinic(?) with  $a:b:c = 1.88:1:2.37$ ,  $\beta = 125^\circ$ .  $H. = 5.5$ .  $G. = 4.25$ . Conchoidal fracture. Decomposed by hot  $\text{H}_2\text{SO}_4$ . Color dark steel gray. Streak brown. Translucent on very thin edges in blood red with  $X < Z$ .  $N_Y = 2.62$  Li;  $N_Z - N_X = \text{moderate}$ . Found in pegmatite at Hackberry, Arizona.

#### 4. Multiple oxides with type formula $A_mB_nX_p$ and $(m + n):p \approx 1:2$

**Betafite**  $[(\text{U,Ca})(\text{Cb,Ta,Ti})_3\text{O}_9 \cdot n\text{H}_2\text{O}]$  is isometric (hexoctahedral?); usually octahedral.  $a$  5.15 Å.  $H. = 4-5.5$ .  $G. = 3.7-5$  (*samirésite*, with Pb, has  $G. = 5.2$ ). Isotropic with  $N = 1.92$  ca. (betafite) to 1.96 (*samirésite*). Color in mass brown (betafite) to yellow (*samirésite*) to black (with Ti). *Djalmaite*<sup>152</sup> is very similar but has much more Ta; it has  $H. = 5.5$ ,  $G. = 5.8$ ,  $N = 1.97$ . Color brown. Found in pegmatite in Madagascar, Siberia, and Norway.

**TAPIOLITE** DITETRAGONAL DIPYRAMIDAL  $c/a = 1.939$   $(\text{Fe,Mn})(\text{Ta,Cb})_2\text{O}_6$

**COMP.** Usually near  $\text{FeTa}_2\text{O}_6$ , but Mn may proxy for Fe probably in any amount and Cb may proxy for Ta at least to  $\text{Cb:Ta} = 3:2$ . Called *mossite* when Cb is dominant. Homeomorphous with rutile; dimorphous with columbite.

**STRUC.** Space group <sup>153</sup>  $P4/mnm$ ;  $a$  4.745,  $c$  9.21 Å. U.C. 2. For mossite:  $a$  4.71,

**PHYS. CHAR.** Crystals prismatic or equant with no good cleavage. Twinning on 013 common.  $H. = 6-6.5$ .  $G. = 7.3-7.8$ ; 8.17 (calc. for  $\text{FeTa}_2\text{O}_6$ ); 6.93 (calc. for  $\text{Cb:Ta} = 1:1$ ).  $F. = 7$ .

**OPT. PROP.** Uniaxial positive with  $N_O = 2.27$  Li,  $N_E = 2.42$ ,  $N_E - N_O = 0.15$  (for a crystal with  $G. = 7.4$ ). Color black. Streak brown. In section yellowish to reddish brown with  $O = \text{pale yellowish or reddish brown}$ ,  $E = \text{nearly opaque}$ .

**OCCUR.** Found in pegmatite and placers, as at Berg, Norway, and Topsham, Maine.

**FERGUSONITE** TETRAGONAL DIPYRAMIDAL<sup>153</sup>  $c/a = 1.464$   $\text{Y}(\text{Cb,Ta})\text{O}_4$

**COMP.** Usually near  $\text{YCbO}_4$ , but Er, Ce, and U commonly proxy for part of Y and Ta proxies for Cb; with Ta dominant it is called *formanite*. With some Ti it is called *risörile*. Sc<sup>154</sup> may proxy for Y.

**STRUC.** Space group <sup>155</sup>  $P4/m(?)$ ;  $a$  7.74,  $c$  11.31 Å. U.C. 8. For artificial  $\text{YTao}_4$ :  $a$  7.75,  $c$  11.41 Å.

**PHYS. CHAR.** Crystals pyramidal or prismatic with 111 cleavage in traces.  $H. = 6$ .  $G. = 5.8$  (to 4.3, if hydrated);  $G. = 3.95$  with much Sc; 5.38 (calc. for  $\text{YCbO}_4$ ), 7.03 (calc. for  $\text{YTao}_4$ ).  $F. = 7$ . Attacked by  $\text{H}_2\text{SO}_4$ .

<sup>152</sup> C. P. Guimarães: *Am. Mineral.*, XXVI, 343 (1941).

<sup>153</sup> V. M. Goldschmidt: *Vid. Sels. Oslo, Mat. Nat. Kl.*, I, 17 (1926).  
c 9.12 Å.

<sup>154</sup> S. R. B. Cooke and E. S. Perry: *Am. Mineral.*, XXX, 623 (1945).

<sup>155</sup> T. Barth: *Norsk Geol. Tidsskr.*, IX, 24 (1926).



**OPT. PROP.** Nearly always isotropic (from alteration) with  $N = 2.06-2.19$  (1.83 with much Sc <sup>154</sup>). Becomes anisotropic on ignition. Sometimes distinctly zoned.<sup>156</sup> When unaltered it is uniaxial negative <sup>157</sup> with strong birefringence. Color in mass gray, yellow, brown, black. Streak brown, gray. In section brown; if anisotropic, weakly pleochroic with  $O > E$ .

**OCCUR.** Found in pegmatite, as at Berg and Risör, Norway; Rockport, Massachusetts, etc.

**Brannerite** [(U,Ca,Fe,Y,Th)<sub>3</sub>Ti<sub>5</sub>O<sub>16</sub>?] is pseudotetragonal <sup>158</sup> prismatic.  $H. = 4.5$ .  $G. = 4.5-5.4$ . Soluble in acid. Isotropic from alteration with  $N = 2.30 \pm 0.02$  Na. Color black. Streak dark greenish brown. Splinters green to reddish brown. Found in placers (in a region of pegmatites) in Kelly Gulch, Idaho.

**Simpsonite** <sup>159</sup> [Al<sub>6</sub>(Ta,Cb)<sub>4</sub>O<sub>19</sub>?] is hexagonal dipyramidal with  $c/a = 0.612$  space group  $C6_3/m$ ;  $a$  7.38,  $c$  4.51 Å. U.C. 1. Crystals basal tablets with common twinning. No good cleavage (or basal cleavage <sup>160</sup>).  $G. = 5.9-7.3$ .  $H. = 7.5$ . Uniaxial negative with  $N_O = 2.0402$ ,  $N_E = 1.9944$  on material from Ecuador;  $N_O - N_E = 0.040-0.045$ . Fluoresces in ultra-violet rays. Found with microlite in pegmatite in Western Australia, Brazil, and Rhodesia.

**COLUMBITE** ORTHORHOMBIC DIPYRAMIDAL (Fe,Mn)(Cb,Ta)<sub>2</sub>O<sub>6</sub>  
 $a:b:c = 0.402:1:0.358$

**COMP.** Columbite has four end-members with continuous variation between them, namely: FeCb<sub>2</sub>O<sub>6</sub> (*ferrocolumbite*), MnCb<sub>2</sub>O<sub>6</sub> (*manganocolumbite*), FeTa<sub>2</sub>O<sub>6</sub> (*ferrotantalite*), and MnTa<sub>2</sub>O<sub>6</sub> (*mangantantalite*).

**STRUC.** Space group <sup>161</sup>  $P_{can}$ , columbite with  $G = 5.71$  has  $a$  5.730,  $b$  14.238,  $c$  5.082 Å. U.C. 4. For mangantantalite:  $a$  5.09,  $b$  14.39,  $c$  5.76 Å.

**PHYS. CHAR.** Crystals short prisms or equant or {010} tablets with good 010 cleavage. Twinning on 201 common.  $H. = 6$  (columbite); 6-6.5 (tantalite).  $G. = 5.0$  (MnCb<sub>2</sub>O<sub>6</sub>) to 7.8 (FeTa<sub>2</sub>O<sub>6</sub>). See Fig. 59.  $F. = 7$ . Insoluble or nearly so.

**OPT. PROP.** The optic plane is 010;  $X = a$ . The optic angle is large; the optic sign is positive in tantalite and probably negative in columbite. The following data are given by Larsen <sup>66</sup> and Macgregor: <sup>162</sup>

<sup>156</sup> C. Frondel, W. H. Newhouse, and R. F. Jarrell: *Am. Mineral.*, XXVII, 730 (1942).

<sup>157</sup> T. Vogt: *Cent. Mineral.*, 1911, 373.

<sup>158</sup> F. L. Hess and R. C. Wells: *Jour. Franklin Inst.*, CLXXXIX, 225 (1920).

<sup>159</sup> H. Bowley and L. E. R. Taylor: *Jour. Roy. Soc. W. Australia*, XXV, 89 and 93 (1939). P. F. Kerr and R. J. Holmes: *Bull. Geol. Soc. Am.*, LVI, 479 (1945). F. H. Pough: *Bull. Geol. Soc. Am.*, LVI, 505 (1945). A. M. Macgregor: *Mineral. Mag.*, XXVII, 157 (1947).

<sup>160</sup> C. P. Guimarães: *Min. Abst.*, IX, 127 (1945). A mineral that is probably simpsonite, but with basal cleavage, is called *calogerasite*.

<sup>161</sup> E. D. Taylor: *Am. Mineral.*, XXV, 123 (1940). P. Quensel: *Geol. För. Förh. Stockholm*, LXVII, 15 (1945).

<sup>162</sup> A. M. Macgregor: *Mineral. Mag.*, XXVII, 157 (1946). The sample seems to be monoclinic?

	Canon City, Colo- rado	Had- dam, Con- necticut	South Dakota	Amelia, Virginia	Alabama	Rho- desia <sup>162</sup>
2V =		(-?)	(+)large	(+)large		(+)34° ±
N <sub>X</sub> =			2.26 ± .02	2.19 ± .01		
N <sub>Y</sub> = 2.45 Li	2.40 Li		2.32 ± .02	2.25 ± .01	2.30-2.40	2.12 ±
N <sub>Z</sub> =			2.43 ± .02	2.34 ± .01		
N <sub>Z</sub> - N <sub>X</sub> = strong	extreme		0.17 ± .04	0.15 ± .02		0.2 ±
G. = 5.48				6.5	7.30	7.7
Est. Ta <sub>2</sub> O <sub>5</sub> = 9.3				43.3	70.0	90.0

Color in mass, black. Streak dark red to black. In thin section the iron types are nearly or quite opaque; the manganese types are very dark red to brown with  $X < Y < Z$ ; for example, in mangantantalite,

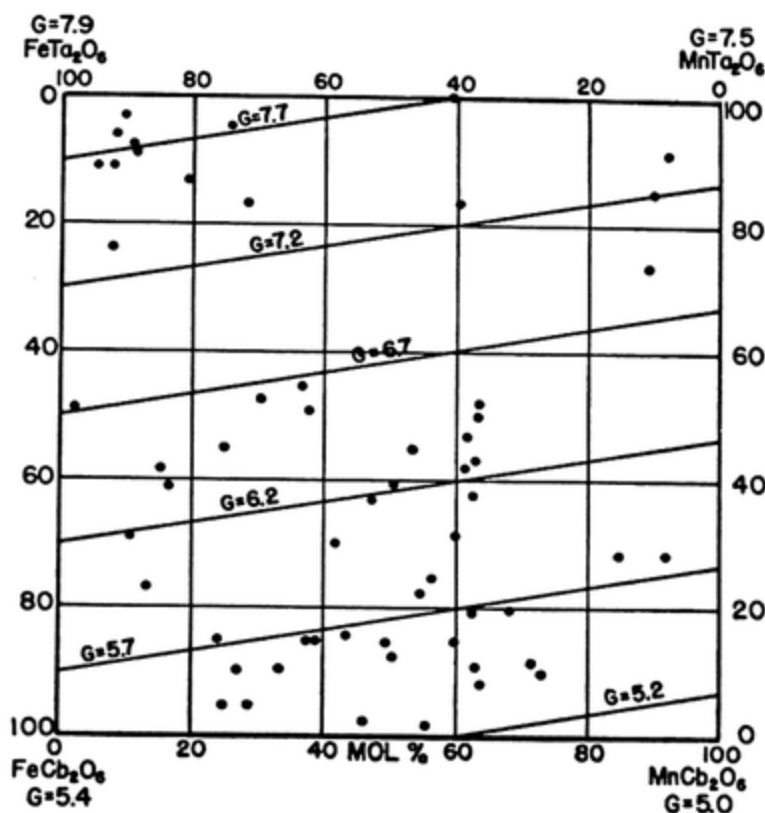


FIG. 59. Variations in composition and specific gravity in columbite. Each dot represents an analysis. Based chiefly on data of Mügge: *Cent. Min.*, p. 417 (1924).

X = pale red, Y = blood red, Z = deep blood red. In polished section <sup>3</sup> gray-white with brownish tint and reddish internal reflections. Reflection percentages: red 14, orange 17, green 15.

OCCUR. Columbite is found sparsely in pegmatite in many places.

DIAG. Columbite is distinguished from wolframite by inferior hardness.

**Fersmite**<sup>163</sup> ( $\text{CaCb}_2\text{O}_6$ ?) is orthorhombic, related to columbite.  $H. = 4.5$ .  $G. = 4.69$ .  $(+?)2V = \text{large}$ .  $N$  about 2;  $N_Z - N_X = \text{moderate}$ . Found in the Urals.

**EUXENITE** ORTHORHOMBIC DIPYRAMIDAL  $(Y, \text{Ca}, \text{Ce}, \text{U}, \text{Th})(\text{Cb}, \text{Ta}, \text{Ti})_2\text{O}_6$   
 $a:b:c = 0.379:1:0.353$

**COMP.** Tantalum may dominate Cb (then called *tanteuxenite*); titanium may dominate both Ta and Cb (then called *polycrase*). A titano-niobate of yttrium and iron has been called *nuevite*.<sup>164</sup>

**PHYS. CHAR.** Crystals prismatic or {010} tablets without cleavage.  $H. = 5-6$ .  $G. = 4.8$  to  $5.9$  (higher with increasing Ta).  $F. = 7$ .

**OPT. PROP.** Isotropic from alteration; or, rarely, *polycrase* is anisotropic<sup>165</sup> with  $(+?)2V = 69^\circ$ ,  $N_X = 2.14$ ,  $N_Y = 2.144$  calc.,  $N_Z = 2.15$ ,  $N_Z - N_X = 0.011$ . Isotropic euxenite has  $N = 2.06$  to  $2.26$ ; index about  $0.1$  higher after ignition. *Nuevite* is isotropic with  $N = 2.23$ , and  $G. = 6.4$ .

Color brown to black in mass; streak yellowish, grayish, or reddish brown. Brown in thin section.

**OCCUR.** Found in pegmatites and placers, as at Rasvåg, Norway; Pomba, Brazil; Morton, Pennsylvania; etc.

**Blomstrandinite**  $[(Y, \text{Er}, \text{Ce}, \text{U}, \text{Fe})(\text{Ti}, \text{Cb})_2\text{O}_6]$  is orthorhombic with  $a:b:c = 0.475:1:0.667$ . Supposed to be dimorphous with euxenite. Crystals {010} tablets or square columnar parallel to  $a$ , with poor 010 cleavage.  $H. = 5.5$ .  $G. = 4.8-5.0$ . Isotropic (from alteration?) with  $N = 2.14$  ca. After ignition  $N = 2.24$ . Color brownish black. Found in pegmatite. Very rare. *Blomstrandite* is not the same, though variable and chemically similar. Isotropic with very high refringence. Color black. Translucent and brown to yellow in thin splinters. Found in pegmatite.

**Yttrocrasite**  $[(Y, \text{Th}, \text{U}, \text{Ce})(\text{Ti}, \text{W})_4\text{O}_{11}]$  is orthorhombic(?) with  $H. = 6$ ,  $G. = 4.8$ ,  $F. = 7$ . Soluble in  $\text{H}_2\text{SO}_4$ . Isotropic from alteration with  $N = 2.12$  to  $2.15$ , or faintly birefringent. Color black; amber to light yellow in thin splinters. Found in pegmatite in Burnet and Llano Counties, Texas.

**Eschynite**  $[(\text{Ce}, \text{Th}, \text{Fe}, \text{Ca})(\text{Cb}, \text{Ti})_2\text{O}_6]$  is orthorhombic dipyramidal with  $a:b:c = 0.487:1:0.674$ . Crystals prisms or {010} tablets.  $H. = 5.5$ ,  $G. = 5.1$ ,  $F. = 7$ . Insoluble in acid. Isotropic from alteration with  $N = 2.20-2.26$ . On ignition becomes birefringent with  $N = 2.285$  ca. Color brownish black; reddish brown in section. *Priorite* is a variety in which Ce is largely replaced by Y; in it  $G. = 4.95$ , and  $N = 2.14$ , increasing to  $2.24$  on ignition. Found in pegmatite, as at Miask, Russia; Hitterö, Norway; etc.

**Samarskite**  $[(Y, \text{Er}, \text{Ce}, \text{U}, \text{Fe}, \text{Ca})(\text{Cb}, \text{Ta})_2\text{O}_6]$  is orthorhombic with  $a:b:c = 0.546:1:0.518$ . Called *yttrotantalite* if  $\text{Ta} > \text{Cb}$ . Crystals elongated along  $c$  with poor 010 cleavage.  $H. = 5-6$ .  $G. = 5.6-5.8$  (with Ti, may reach  $6.2$ ).  $F. = 5$ . Nearly insoluble in acids. Isotropic from alteration (metamict) with  $N = 2.10$  to  $2.25$ . Also birefringent. Color velvet black to brown. Streak dark brown to black; also gray; in section brownish to opaque. *Wiikite* is altered material, at least in part

<sup>163</sup> E. M. Bohnstedt and T. A. Burova: *C. R. Acad. Sci. U.R.S.S.*, LII, 69 (1946); *Chem. Abst.*, XLI, 1956 (1947); *Min. Abst.*, X, 102 (1947).

<sup>164</sup> J. Murdoch: *Bull. Geol. Soc. Am.*, LVII, 1219 (1946).

<sup>165</sup> O. H. Leonardos: *Minis. Agric. Brazil, Bull.* 11, 26 (1936).

related to samarskite; it has  $N = 1.96-2.04$ ; birefringent in spots. Samarskite is found in pegmatite, as at Miask, Russia; Nuevo, California; etc.

**Hjelmite**  $[(Y, Fe, U, Mn, Ca)(Cb, Ta, Sn)_2O_6]$  is orthorhombic(?) with <sup>166</sup>  $a:b:c = 0.465:1:1.026$ . Crystals rough with no cleavage.  $H. = 5$ .  $G. = 5.2-5.8$ .  $F. = 7$ . Uniaxial (or nearly so) and positive with  $N_O = 2.30 \pm 0.02$ ,  $N_E = 2.40 \pm 0.04$ ,  $N_E - N_O = 0.10$ . Color black; streak grayish black to brownish green. In section pleochroic with  $O =$  yellowish brown,  $E =$  nearly opaque. Found in pegmatite, as near Fahlun and Norberg, Sweden.

**Ampangabéite**  $[(U, Y, Ce, Th)_2(Cb, Ta, Fe, Ti)_7O_{18}]$  is probably orthorhombic; short rectangular crystals with no cleavage.  $H. = 4$ .  $G. = 3.8-4.6$ , decreasing with alteration. Fuses to a brown slag. Partly soluble in HCl. Isotropic from alteration with  $N = 2.13 \pm 0.03$ . Color brown to black; in section red-brown to opaque. Found only in pegmatite in Madagascar.

**Fourmarierite** <sup>167, 168</sup>  $(PbO \cdot 4UO_3 \cdot 7H_2O?)$  is orthorhombic with  $a:b:c = 0.868:1:0.842$ ;  $a$  14.5,  $b$  16.7,  $c$  14.1 Å. Crystals are {100} tablets with good 100 cleavage.  $H. = 3-4$ .  $G. = 5.74$ . The optic plane is 001 with  $X = a$ .  $(-)2E =$  large,  $r > v$  strong.  $N_X = 1.85$ , <sup>66, 167</sup>  $N_Y = 1.92$ ,  $N_Z = 1.94$ ,  $N_Z - N_X = 0.09$ ,  $N_X = 1.77$ .<sup>169</sup> Color red with  $X =$  dark red-brown to colorless,  $Y =$  red-brown to pale yellow,  $Z =$  dark red-brown to yellow. Found in uranium ores in the Belgian Congo.

**Curite**  $(2PbO \cdot 5UO_3 \cdot 4H_2O?)$  is orthorhombic<sup>22</sup> with  $a:b:c = 0.955:1:0.654$ ;  $a$  12.52,  $b$  12.98,  $c$  8.35. Crystals acicular with good 100 cleavage.  $H. = 4-5$ .  $G. = 7.2$ . Soluble in acids. The optic plane is 100;  $X = b$ .  $(-)2V =$  large,  $r > v$  strong.  $N_X = 2.06$ ,  $N_Y = 2.11$ ,  $N_Z = 2.15$ ,  $N_Z - N_X = 0.09$ . Color orange-red; streak orange. In section yellow to reddish orange with  $X =$  pale yellow,  $Y =$  light red-orange,  $Z =$  dark red-orange. Found in the Belgian Congo.

**Uranospherite**  $(Bi_2O_3 \cdot 2UO_3 \cdot 3H_2O?)$  is probably orthorhombic. Crystals fibrous in spherulites. Good 100 cleavage.  $H. = 2-3$ .  $G. = 6.36$ . Decrepitates on heating. The optic plane is 010;  $X = a$ .  $(+)2V =$  large,  $r < v$ , strong.  $N_X = 1.955$ ,  $N_Y = 1.985$ ,  $N_Z = 2.05$ ,  $N_Z - N_X = 0.095$ . Color orange-yellow to brick-red. Streak yellow. Found in Saxony.

## STIBIOTANTALITE

ORTHORHOMBIC PYRAMIDAL

$Sb(Ta, Cb)O_4$

$a:b:c$  <sup>170</sup>  $= 0.417:1:0.470$

COMP.  $SbTaO_4$  probably forms a complete series with  $SbCbO_4$ , the latter being called *stibiocolumbite*.

STRUC. Space group *Pcn*,  $a$  4.916,  $b$  11.78,  $c$  5.542 Å. U.C. 4.

PHYS. CHAR. Crystals prismatic or {100} plates, with good 010 cleavage. Lamellar twinning on 100.  $H. = 5$ .  $G. = 5.68$  ( $SbCbO_4$ ) to 7.53 ( $SbTaO_4$ ).  $F. = 4$ . Insoluble except in HF. Strongly pyroelectric.

<sup>166</sup> Crystals are poorly defined;  $b$  and  $c$  axes may be equal and the mineral tetragonal—it is uniaxial (or very nearly so).

<sup>167</sup> H. Brasseur: *Min. Abst.*, IX, 230 (1946); *Am. Mineral.*, XXXIII, 619 (1948).

<sup>168</sup> V. Billiet: *Bull. Soc. Fr. Min.*, XLIX, 136 (1926).

<sup>169</sup> H. Brasseur: *Bull. Soc. Roy. Sci. Liège*, No. 12, December, 1946.

<sup>170</sup> C. Palache and F. A. Gonyer: *Am. Mineral.*, XXV, 411 (1940); K. Dihlstrom: *Zeit. anorg. Chem.*, CCXXXIX, 57 (1938), X-ray  $b$  and  $c$  interchanged to make  $b > a$ .

OPT. PROP. The optic plane is 010;  $X = a$ .  $(+ )2V = 71^{\circ}\text{--}78^{\circ}$ ,  $r < v$  strong. On the basis of only two measures,<sup>171</sup> for Na light:  $N_X = 2.345\text{--}2.425$ ,  $N_Y = 2.382\text{--}2.437$ ,  $N_Z = 2.452\text{--}2.462$ ,  $N_Z - N_X = 0.107\text{--}0.037$ . See Fig. 60. With increase

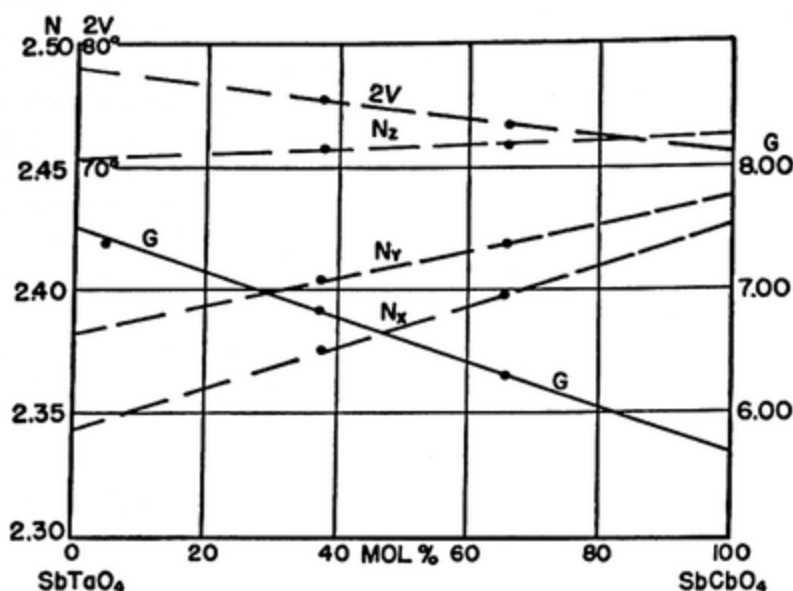


FIG. 60. Properties of stibiotantalite.

in Cb, the specific gravity and optic angle (except for Tl?) decrease and the refraction and dispersion increase, as shown in the tabulation.

At. % Cb	38 (est.)			66.5 (est.)		
	Li	Na	Tl	Li	Na	Tl
$N_X =$	2.3470	2.3742	2.4014	2.3686	2.3977	2.4261
$N_Y =$	2.3750	2.4039	2.4342	2.3876	2.4190	2.4508
$N_Z =$	2.4275	2.4568	2.4876	2.4280	2.4588	2.4903
$N_Z - N_X =$	0.0800	0.0826	0.0862	0.0594	0.0611	0.0642
$(+)2V$ (calc.) =	$73^{\circ} 40'$	$75^{\circ} 5'$	$77^{\circ} 38'$	$70^{\circ} 0'$	$73^{\circ} 25'$	$77^{\circ} 50'$

Color dark brown to light brown, reddish or yellow. Streak yellow to brown. In section pale yellow-brown to brown; some crystals vary in color in zones.

OCCUR. Found in pegmatite, and in placers, as at Greenbushes, Western Australia; Varutrask, Sweden; Topsham, Maine; Mesa Grande, California.

**Bismutotantalite**  $[\text{Bi}(\text{Ta}, \text{Cb})\text{O}_4]$  is orthorhombic with  $a:b:c = 0.427:1:0.485$ . Crystals prismatic with 101 and  $10\bar{1}$  partings.  $H. = 5$ .  $G. = 8\text{--}8.4$ . Insoluble except in HF. All indices above 2.2. Birefringence about 0.1 to 0.15. Color black like coal. Streak black. In thin section light gray to colorless with parallel extinction. Found in pegmatite at Gamba Hill, Uganda.

**Yttrotantalite**  $[(\text{Y}, \text{Fe}, \text{U}, \text{Ca})(\text{Ta}, \text{Cb})\text{O}_4]$  is orthorhombic<sup>172</sup> with  $a:b:c = 0.557:1:0.517$ . Crystals prismatic with poor 010 cleavage.  $H. = 5\text{--}5.5$ .

<sup>171</sup> S. L. Penfield and W. E. Ford: *Am. Jour. Sci.*, CLXXII, 61 (1906).

<sup>172</sup> W. C. Brögger: *Die Mineralien der süd-norweg. Granitpegmatitgänge*, Pt. 1, 153 (1906).

G. = 5.5–5.9. F. = 7. Insoluble in acids. Isotropic from alteration with  $N = 2.15 \pm 0.02$ . Color black to yellow; streak gray. Red-brown in section. Found in pegmatite, as at Hattavik, Norway.

**Polymignite** [(Y,Ce,Ca,Zr)(Cb,Ta,Ti)O<sub>4</sub>?] is orthorhombic dipyramidal with  $a:b:c = 0.712:1:0.512$ . Crystals prismatic with 100 and 010 cleavages in traces. H. = 6.5. G. = 4.8. F. = 7. Isotropic from alteration with  $N = 2.22 \pm 0.01$ . Color black. Streak dark brown. Reddish brown in section. Found in pegmatite, as at Fredricksvarn, Norway.

**Uvanite** <sup>173</sup> (2UO<sub>3</sub>·3V<sub>2</sub>O<sub>5</sub>·15H<sub>2</sub>O) is orthorhombic with two pinacoidal cleavages. Soluble in ammonium carbonate solution. (+)2V = 52°;  $N_X = 1.817$ ,  $N_Y = 1.879$ ,  $N_Z = 2.057$ ,  $N_Z - N_X = 0.24$ . Color brownish yellow with X = light brown to yellow, Y = dark brown, Z = greenish yellow. Found in Emery County, Utah.

**Fernandinite** <sup>174</sup> (CaO·V<sub>2</sub>O<sub>4</sub>·5V<sub>2</sub>O<sub>5</sub>·14H<sub>2</sub>O?) is fibrous; rarely in rectangular plates. Soluble in acid to a green solution.  $N_Y = 2.05$ ,  $N_Z - N_X = \text{strong}$ . Color dull green, not pleochroic. Found at Minasragra, Peru.

**α-Uranopilite** <sup>175</sup> (6UO<sub>3</sub>·SO<sub>3</sub>·16H<sub>2</sub>O?) is triclinic(?). Crystals tiny laths with perfect 010 cleavage. G. = 3.9. Soluble in acid. Extinction (Y') on 010 is at 15°(–18°) to elongation and X is somewhat inclined to a normal to 010. (+)2V = large with  $r < v$  extreme. {010} plates give sharp extinction in white light; others give very abnormal interference colors.  $N_X = 1.623$ ,  $N_Y = 1.625$ ,  $N_Z = 1.633$ ,  $N_Z - N_X = 0.010$ . Color lemon yellow in section and not pleochroic. Found in Bohemia.

**β-Uranopilite** (6UO<sub>3</sub>·SO<sub>3</sub>·10H<sub>2</sub>O) is probably orthorhombic.<sup>175</sup> It has parallel extinction, elongation along Y, and Z in 010. (–)2V = small.  $N_X = 1.72$ ,  $N_Y = 1.76$ ,  $N_Z = 1.76$ ,  $N_Z - N_X = 0.04$ . Color grayish, or dirty green. Found in Bohemia.

**Melanovanadite** <sup>176</sup> [2CaO·2V<sub>2</sub>O<sub>4</sub>·3V<sub>2</sub>O<sub>5</sub>( $n$ H<sub>2</sub>O?)] is monoclinic with  $a:b:c = 0.474:1:0.582$ ,  $\beta = 91^\circ 22'$ . Crystals prismatic with perfect 010 cleavage. H. = 2.5. G. = 3.48. F. = easy. Soluble in acid. The optic plane is normal to 010;  $X \wedge c = 75^\circ$ . (–)2V = small.  $N_X = 1.73$ ,  $N_Y = 1.96$ ,  $N_Z = 1.98$ ,  $N_Z - N_X = 0.25$ . Color black with X = yellowish brown, Y = dark reddish brown, Z = dark reddish brown, nearly opaque. Found in an ore deposit at Minasragra, Peru.

**Zippeite** (2UO<sub>3</sub>·SO<sub>3</sub>· $n$ H<sub>2</sub>O) is probably monoclinic; crystals {010} laths with vertical elongation and distinct 010 cleavage. H = 3. Soluble in acid.  $X = b$ ;  $Z \wedge c = 32^\circ$  to  $40^\circ$  in obtuse angle  $\beta$ . (–)2V = large, dispersion slight.  $N_X = 1.630$ ,  $N_Y = 1.689$ ,  $N_Z = 1.739$ ,  $N_Z - N_X = 0.109$ ; also  $N_X = 1.630$ ,  $N_Y = 1.700$ ,  $N_Z = 1.720$ ,  $N_Z - N_X = 0.090$ . Also <sup>177</sup>  $N_X = 1.575$ – $1.636$ ,  $N_Y = 1.615$ – $1.694$ ,  $N_Z = 1.646$ – $1.732$ ,  $N_Z - N_X = 0.071$ – $0.096$ . Color orange, yellow, etc., with X = nearly colorless, Y = rather deep yellow, Z = deep yellow. Found with pitchblende, as at Great Bear Lake, Canada.

<sup>173</sup> F. L. Hess and W. T. Schaller: *J. Wash. Acad. Sci.*, IV, 576 (1914).

<sup>174</sup> W. T. Schaller: *J. Wash. Acad. Sci.*, V, 7 (1915). Are fernandinite, melanovanadite, and uvanite vanadates rather than multiple oxides?

<sup>175</sup> R. Nováček: *Am. Mineral.*, XX, 813 (1935). Are uranopilite, zippeite, johannite, and uranochalcite sulfates rather than multiple oxides?

<sup>176</sup> W. Lindgren: *Am. Jour. Sci.*, CCI, 195 (1922); T. Barth and H. Berman: *Chem. Erde*, V, 22 (1930).

<sup>177</sup> R. Nováček: *Min. Abst.*, VI, 148 (1935).



**Hydrocalumite** <sup>178</sup> [ $\text{Ca}_4\text{Al}_2(\text{OH})_{14} \cdot 7\text{H}_2\text{O}$ ] is monoclinic sphenoidal with  $a:b:c = 0.842:1:1.477$ ,  $\beta = 111^\circ$  (pseudo-hexagonal). Space group  $P2_1$ ;  $a$  9.6,  $b$  11.4,  $c$  16.84 Å. U.C. 4. Perfect 001 cleavage; poor cleavage at about  $60^\circ$  to 100. Strongly pyroelectric.  $H. = 3$ .  $G. = 2.15$ . The optic plane is 010;  $X \wedge c < 3^\circ$ .  $(-)2V = 24^\circ$ ,  $N_X = 1.535$ ,  $N_Y = 1.553$ ,  $N_Z = 1.557$ ,  $N_Z - N_X = 0.022$ . Becomes uniaxial at  $90^\circ$ – $95^\circ$ . Colorless to green in mass. Loses water on heating. Found in a contact zone at Scawt Hill, Ireland. A very similar compound has been made in Portland-cement studies.

**Johannite** <sup>177,179</sup> ( $\text{CuO} \cdot \text{UO}_3 \cdot \text{SO}_3 \cdot 4\text{H}_2\text{O}$ ?) is triclinic with  $a:b:c = 0.821:1:0.553$ ,  $\alpha = 124^\circ 56'$ ,  $\beta = 69^\circ 24'$ ,  $\gamma = 132^\circ 56'$ . Crystals {100} tablets elongated along  $c$ , with 001 cleavage and two sets of lamellar twinning.  $H. = 2$ .  $G. = 3.3$ .  $F. = 3$ . Soluble in water.  $X$  is near  $a$  and  $Y \wedge c = 5^\circ$ – $8^\circ$ , with marked dispersion. Crystals lying on 010 have extinction at  $5^\circ$ – $7^\circ$  to edge.  $X$  is at  $-101^\circ(\phi)$  and  $85^\circ(\rho)$ .  $Y$  is at  $37^\circ(\phi)$  and  $8^\circ(\rho)$ .  $(+)2V =$  very large,  $r < v$  strong, or  $(-)2V =$  very large,  $r > v$  strong.  $N_X = 1.572$ – $1.577$ ,  $N_Y = 1.592$ – $1.597$ ,  $N_Z = 1.611$ – $1.616$ ,  $N_Z - N_X = 0.036$ – $0.042$ . Color yellow to black with  $X < Y < Z$ ;  $X =$  colorless,  $Y =$  pale yellow,  $Z =$  canary yellow. Found with copper ore and with pitchblende, as at Joachimsthal, Bohemia.

**Uranochalcite** ( $\text{UO}_3 \cdot \text{SO}_3 \cdot \text{CaO} \cdot \text{CuO} \cdot \text{H}_2\text{O}$ ) is fibrous.  $H. = 2$ – $2.5$ . Soluble in acid.  $Z = c$  (parallel to fibers).  $(+)2V =$  small;  $N_X = 1.655$ ,  $N_Y = 1.655$ ,  $N_Z = 1.662$ ,  $N_Z - N_X = 0.007$ . Abnormal interference colors. Color green with  $X$  and  $Y =$  pale yellowish green,  $Z =$  pale greenish yellow. Found at Joachimsthal, Bohemia.

**Thoreaulite** <sup>180</sup> ( $\text{SnTa}_2\text{O}_7$ ) is monoclinic(?) with perfect 100 and imperfect 001 cleavages.  $H. = 6$ .  $G. = 7.6$ – $7.9$ . The optic plane is 010;  $Z \wedge c = 27^\circ$ .  $(+)2V = 25^\circ$ ; mean index = 2.38 *ca.*; birefringence on 100 = 0.039. (If  $N_Y = 2.38$ ,  $N_X = 2.377$  calc.,  $N_Z = 2.43$  calc.,  $N_Z - N_X = 0.053$  calc.). For <sup>181</sup>  $\lambda = 509$ ,  $N_Y = 2.459$ ; for 585,  $N_Y = 2.417$ ; for 640,  $N_Y = 2.408$ . Again: <sup>182</sup>  $Z \wedge c = 32^\circ$ ,  $(+)2V = 30^\circ$ – $35^\circ$ ,  $N_X = 2.39$ ,  $N_Z = 2.52$ . Color brown in mass; streak yellow with greenish tint. In section yellow. Found in Belgian Congo.

**Vandenbrandeite** ( $\text{CuO} \cdot \text{UO}_3 \cdot 2\text{H}_2\text{O}$ ) is probably triclinic with perfect basal(?), distinct pinacoidal(?), and poor domatic(?) cleavages.  $H. = 4$ .  $G. = 5$ . Soluble in warm acid. An optic axis is nearly normal to basal cleavage.  $Z \wedge$  elongation =  $40^\circ \pm$ .  $(-)2V =$  large with strong dispersion giving abnormal interference colors.  $N_X = 1.76$  (Thoreau <sup>183</sup>); 1.77 (Schoep <sup>184</sup>).  $N_Y = 1.78 \pm 0.02$ ,  $N_Z = 1.80 \pm 0.02$ ,  $N_Z - N_X = 0.24 \pm 0.02$ . Color in mass dark green to nearly black. Streak green. In section strongly pleochroic, from colorless to green. A secondary mineral in ores of the Belgian Congo.

<sup>178</sup> C. E. Tilley: *Mineral. Mag.*, XXIII, 607 (1934); G. Assarsson: *Zeit. anorg. Chem.*, CCXXII, 321 (1935).

<sup>179</sup> E. S. Larsen and H. Berman: *Am. Mineral.*, XI, 1 (1926);  $a$  and  $b$  interchanged to make  $b > a$ .

<sup>180</sup> J. Mélon: *Bull. Acad. Roy. Belg.*, Cl. Sci., 1935, 473. *Min. Abst.*, VI, 153 (1935).

<sup>181</sup> R. Bailly: *Soc. Geol. Belg.*, LXV, No. 6 (1942).

<sup>182</sup> G. P. Barsanov and A. I. Ginsberg: *Min. Abst.*, X, 247 (1948).

<sup>183</sup> J. Thoreau: *Ann. Soc. Geol. Belg.*, LV, C3 (1933).

<sup>184</sup> A. Schoep: *Ann. Mus. Congo Belg.*, I, No. 3, 25 (1932); *N. J. Min.*, I, 250 (1933); *Min. Abst.*, V, 292 (1933).

**Clarkeite** <sup>185</sup> ( $\text{RO} \cdot 3\text{UO}_3 \cdot 3\text{H}_2\text{O}$ , with  $\text{R} = \text{Na}_2, \text{Pb}, \text{Ca}$ , etc.) is a hydrothermal alteration product of uraninite. No cleavage.  $\text{H.} = 4\text{--}4.5$ .  $\text{G.} = 6.39$ . Soluble in  $\text{HCl}$ .  $(-)\text{2V} = 30^\circ\text{--}50^\circ$ ,  $r < v$  weak.  $\text{N}_\text{X} = 1.997$ ,  $\text{N}_\text{Y} = 2.098$ ,  $\text{N}_\text{Z} = 2.108$ ,  $\text{N}_\text{Z} - \text{N}_\text{X} = 0.111$ . Color dark reddish brown in mass; orange, with slight pleochroism in thin section. Found at Spruce Pine, North Carolina, as an alteration product of uraninite.

<sup>185</sup> C. S. Ross, E. P. Henderson, and E. Posnjak: *Am. Mineral.*, XVI, 213 (1931).

## V. CARBONATES

This division includes all natural carbonates whose optical properties are known. Nitrates are added because some of them are crystallographically very similar to carbonates. Finally, the rare iodates are included. The arrangement is in the order of increasing A to B ratio. An outline follows:

1. Type formula  $\approx A_2(BX_3)_3$ .
2. Type formula  $ABX_3$ .
  - a. Without additional anions.
  - b. With additional anions  $\begin{cases} \text{Anhydrous.} \\ \text{Hydrous.} \end{cases}$
3. Type formula  $\approx A_3(BX_3)_2$ .
  - a. Without additional anions.
  - b. With additional anions.
4. Type formula  $\approx A_2BX_3$ .
  - a. Without additional anions.
  - b. With additional anions.
5. Type formula  $\approx A_3BX_3$ .
6. Nitrates.
7. Iodates.

### 1. Carbonates with type formula $\approx A_2(BX_3)_3$

**Lanthanite**  $[(La, Di, Ce)_2(CO_3)_3 \cdot 8H_2O]$  is orthorhombic dipyramidal with  $a:b:c = 0.94:1:0.89$ . Crystals thin basal plates with perfect 001 cleavage.  $H. = 3$ .  $G. = 2.6-2.74$ .  $F. = 7$ . Soluble in acid with effervescence. The optic plane is 100;  $X = c$ .  $(- )2V = 62^\circ$ ,  $r < v$  weak.  $N_X = 1.52$ ,  $N_Y = 1.587$ ,  $N_Z = 1.613$ ,  $N_Z - N_X = 0.093$ . Color white. Found in zinc and iron ore deposits in New York, Pennsylvania, etc.

**Tengerite**<sup>1</sup> is a hydrous carbonate of Y, Ca, Be, etc., of uncertain formula. It is fibrous or powdery. Soluble in acid with effervescence. Axis X parallel to elongation.  $(+)2V = \text{large}$ ,  $N_X = 1.555$ ,  $N_Y = 1.57$ ,  $N_Z = 1.585$ ,  $N_Z - N_X = 0.030$ . Again,<sup>1</sup>  $G. = 3.12$ ,  $N_X = 1.622$ ,  $N_Y = ?$ ,  $N_Z = 1.642$ ,  $N_Z - N_X = 0.020$ . Color white. Found with gadolinite in Texas; also in Japan.

**Uranothallite**  $[Ca_2U(CO_3)_4 \cdot 10H_2O]$  is orthorhombic with  $a:b:c = 0.954:1:0.783$ . Crystals indistinct, in crusts, with distinct 100 cleavage.  $H. = 2.5-3$ .  $F. = 7$ . Soluble in acid with effervescence. Axis  $X = a$ .  $(+)2V = 37^\circ-42^\circ$ ,  $r > v$  weak.

<sup>1</sup>T. Iimori (*Min. Abst.*, VII, 357, 1939) gives the formula:  $3YOHCO_3 \cdot CaCO_3 \cdot 3H_2O$ .

$N_X = 1.500$ ,  $N_Y = 1.503$ ,  $N_Z = 1.537$ ,  $N_Z - N_X = 0.037$ . Color green. *Liebigite* is probably a synonym.<sup>2</sup> Uranothallite is an alteration product of uraninite. Found in Bohemia.

**Voglite** is a hydrous carbonate of U, Ca, Cu of unknown formula. It is triclinic(?), in scales. Lamellar twinning parallel to scales. Soft.  $F. = 7$ . Soluble in acid with effervescence. Axis X is nearly normal <sup>2a</sup> to scales in which  $Z' \wedge$  elongation =  $33^\circ$ .  $(+)2V = 60^\circ$ ,  $r < v$  very strong.  $N_X = 1.541$ ,  $N_Y = 1.547$ ,  $N_Z = 1.564$ ,  $N_Z - N_X = 0.023$ . Color emerald green with X and Y = deep bluish green, Z = pale yellowish. Voglite is an alteration product of uraninite at Joachimsthal, Bohemia.

**Studtite** is a hydrous uranium carbonate <sup>2b</sup> of unknown formula. It is orthorhombic in flexible fibers with  $Z \parallel$  length.  $(+)2V =$  small,  $N_X = 1.545$ ,  $N_Y = 1.555$ ,  $N_Z = 1.68$ ,  $N_Z - N_X = 0.135$ . Color yellow. Found in Katanga, Belgian Congo.

**Diderichite** is a slightly hydrated uranium carbonate <sup>2b</sup> of unknown formula. It is orthorhombic. Yellow-green fibers.  $(+)2V =$  large,  $N_X > 1.722$ ,  $N_Y = 1.728$ ,  $N_Z < 1.74$ ,  $N_Z - N_X < 0.018$ .

## 2. Carbonates with type formula $ABX_3$

### (a) WITHOUT ADDITIONAL ANIONS

#### CALCITE GROUP

The minerals <sup>3</sup> of the calcite group are carbonates of divalent metals having hexagonal scalenohedral symmetry. Crystals are commonly rhombohedral in aspect, but calcite exhibits a remarkable variety of crystal habits. All the minerals of the group are often compact, fibrous, or granular; rarely lamellar, or stalactitic. They have perfect rhombohedral cleavage, and a hardness of 3 to 5; they are uniaxial and negative with extreme birefringence. The chief species and subspecies are the following:

Species	Subspecies	$c/a$	Cleavage Angle	Composition
Calcite		0.8543	$74^\circ 55'$	$\text{CaCO}_3$
Brownspar	Magnesite	0.8095	$72^\circ 30'$	$\text{MgCO}_3$
	Siderite (Chalybite)	0.8184	$73^\circ 0'$	$\text{FeCO}_3$
	Rhodochrosite	0.8259	$73^\circ 9'$	$\text{MnCO}_3$
	Smithsonite	0.8063	$72^\circ 20'$	$\text{ZnCO}_3$
	Spherocobaltite	0.81		$\text{CoCO}_3$

The variations in optic properties and estimated limits of mutual solubilities <sup>4</sup> are shown in Fig. 61 for that part of the calcite group (and dolomite) having  $\text{CaCO}_3$  as one end-member.

<sup>2</sup> E. S. Larsen: *Am. Mineral.*, II, 87 (1917).

<sup>2a</sup> E. S. Larsen: *U. S. Geol. Surv. Bull.* 679 (1921) and 848 (1934).

<sup>2b</sup> J. F. Vaes: *Ann. (Bull.) Soc. Geol. Belg.*, LXX, B212 (1947).

<sup>3</sup> Dolomite is usually considered to be a member of the calcite group, but it has different symmetry.

<sup>4</sup> P. Krieger: *Am. Mineral.*, XV, 23 (1930); R. G. Wayland: *Am. Mineral.*, XXVII, 614 (1942); W. E. Ham and M. C. Oakes: *Econ. Geol.*, XXXIX, 425 (1944).

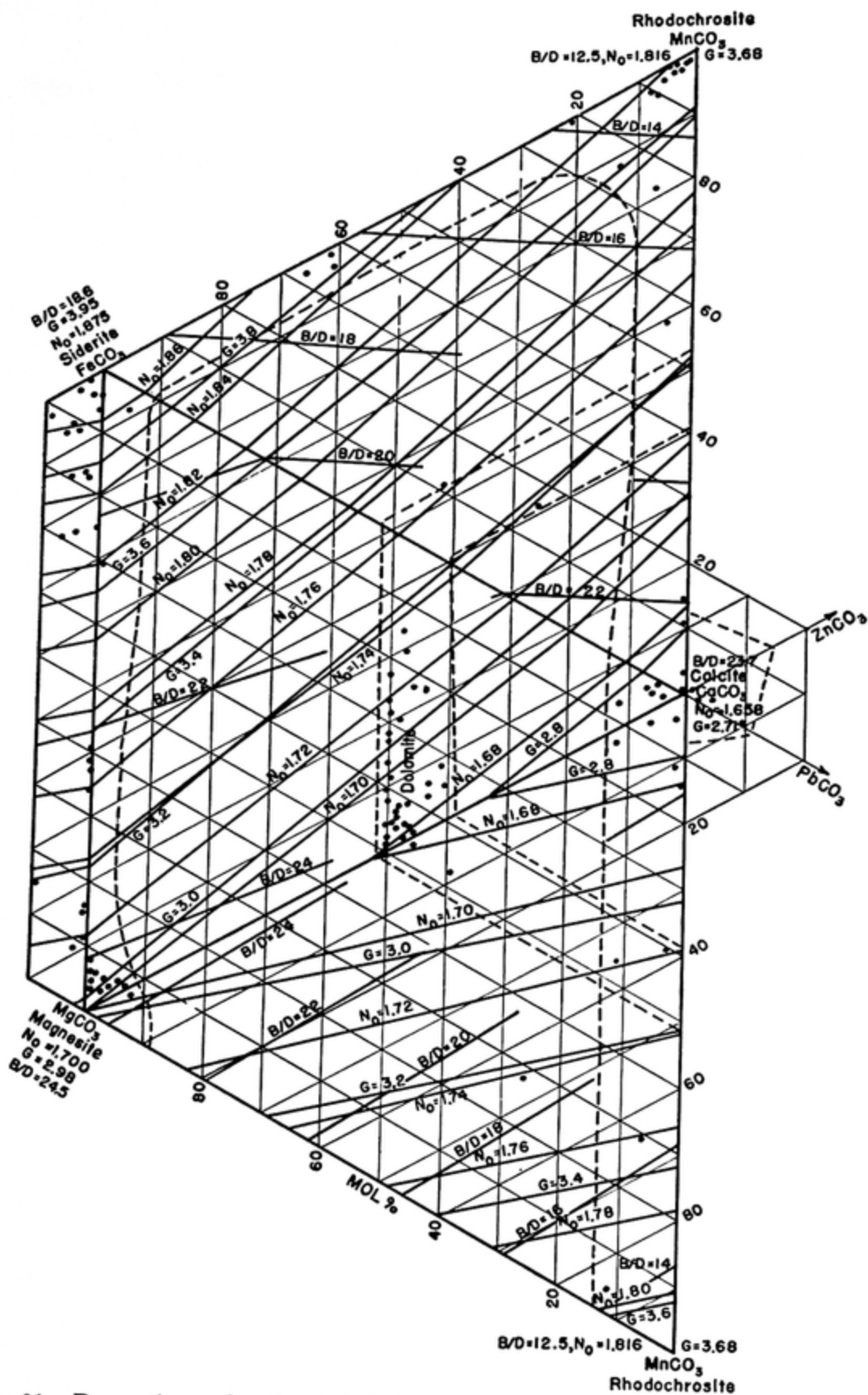
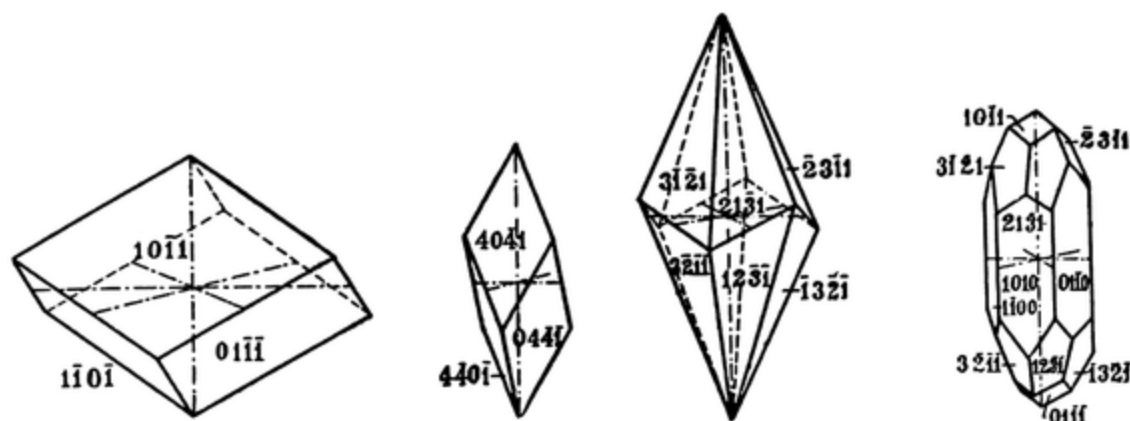


FIG. 61. Properties and estimated limits of mutual solubilities in that part of the calcite group which has  $\text{CaCO}_3$  as one end-member. Each dot represents an analysis and dash lines represent estimated limits of mix-crystal formation. Dolomite is also included.

**CALCITE** HEXAGONAL SCALENOHEDRAL  $c/a = 0.8543$   $\text{CaCO}_3$

**COMP.** Calcite is usually (very nearly) pure  $\text{CaCO}_3$ , but Mn may proxy for Ca to at least about <sup>4</sup> 70 atomic per cent; Pb, Mg, or Fe to



FIGS. 62-65. Crystal habits of calcite.

about 10 or 15 per cent. In rare cases Zn, Co, Sr, or Ba may be present in small amount.

**STRUC.** Space group  $R\bar{3}c$ ;  $a$  6.36,  $\alpha_{rh}$   $46^\circ 6'$ . U.C. 2.

**PHYS. CHAR.** Crystals of extreme diversity of habit, sometimes highly complex; often rhombohedral in aspect; also scalenohedral. See Figs. 62-65. Twinning on 0001; also lamellar on 0112, probably due in part to strains in grinding as such twins are easily produced artificially as described on page 21 of Part I. Other types of twinning less common. Perfect  $10\bar{1}1$  cleavage. See Fig. 66.  $H. = 3$ .  $G. = 2.715$ .  $F. = 7$ , but dissociates at  $900^\circ \text{C}$ . Under a pressure of 170 atmospheres of  $\text{CO}_2$  calcite inverts at  $970^\circ \text{C}$ . and fuses at  $1290^\circ \text{C}$ . Easily soluble in cold dilute acid with effervescence.

**OPT. PROP.** Uniaxial negative with extreme birefringence.

	C 656	D 589	F 486	F - C
$N_O =$	1.6544	1.6584	1.6679	0.0135
$N_E =$	1.4847	1.4864	1.4907	0.0060
$N_O - N_E =$	0.1697	0.1720	0.1772	0.0075

$N_E'$  on the cleavage of calcite is 1.566.  $N_E$  and the probable composition can be obtained approximately for any rhombohedral carbonate from  $N_E'$  or  $N_O$  by the use of Fig. 75.

Calcite with 1.9 per cent of  $\text{PbCO}_3$  has <sup>5</sup>  $N_O = 1.6668$ ,  $N_E = 1.4904$ .

<sup>5</sup> W. L. Brown: *U. Toronto Geol. Stud.*, 36, 45 (1934).



$CaCO_3$  with variable tenor of  $MnCO_3$  has (see Fig. 67):

$MnCO_3\%$ = 6.5 <sup>5</sup>	7.0 <sup>6</sup>	11.0 <sup>7</sup>	15.4 <sup>6</sup>	22.5 <sup>5</sup>	32.3 <sup>6</sup>	42.2 <sup>6</sup>	68.8 <sup>8</sup>
$N_O$ = 1.6677	1.672	1.680	1.680	1.6919	1.713	1.721	1.763
$N_E$ =	1.501	1.502	1.503		1.519	1.534	
$N_E'$ on (1011) =	1.574 <sup>8a</sup>	1.580 <sup>8a</sup>	1.580 <sup>8a</sup>		1.608 <sup>8a</sup>	1.622 <sup>8a</sup>	
$N_O - N_E$ =	0.171	0.178	0.177		0.194	0.187	
$G.$ = 2.78	2.824	2.812	2.856	2.945	3.02	3.14	

Calcite is usually white or colorless but may be any color; with  $MnCO_3$  it is often pink. Colorless in section.

**INVER.** Calcite is the stable form of  $CaCO_3$  under ordinary conditions. Aragonite is a metastable form; aragonite<sup>9</sup> and  $\mu$ - $CaCO_3$  (or vaterite) crystallize from solution at temperatures up to 90° C. Vaterite is not known in nature; it is hexagonal with  $G.$  = 2.54; uniaxial positive with  $N_O$  = 1.550,  $N_E$  = 1.650,  $N_E - N_O$  = 0.100.

**ALTER.** Calcite is slowly soluble in surface waters but otherwise quite stable.

**OCCUR.** Calcite is not only the chief constituent of all kinds of limestone (except dolomitic) and marble but also is very common in veins and ore deposits, as well as in igneous rocks, where it is nearly always an alteration product.

**DIAG.** Extremely strong birefringence, uniaxial negative character, relief commonly visibly varying from moderate to low on rotation, and rhombohedral cleavages with parallel lamellar twinning are diagnostic characters in thin section. Calcite differs from other members of the group, except magnesite, in having one index lower than that of Canada balsam. It differs from magnesite and dolomite in its very ready solubility in cold dilute acid, its low specific gravity, and its common lamellar twinning. Dolomite often shows crystal boundaries. A method of distinction based on staining is described on page 43 of Part I.

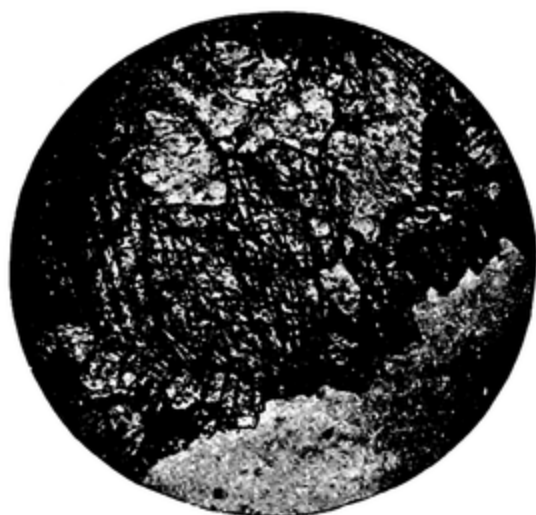


FIG. 66. Photomicrograph of calcite showing three directions of cleavage.

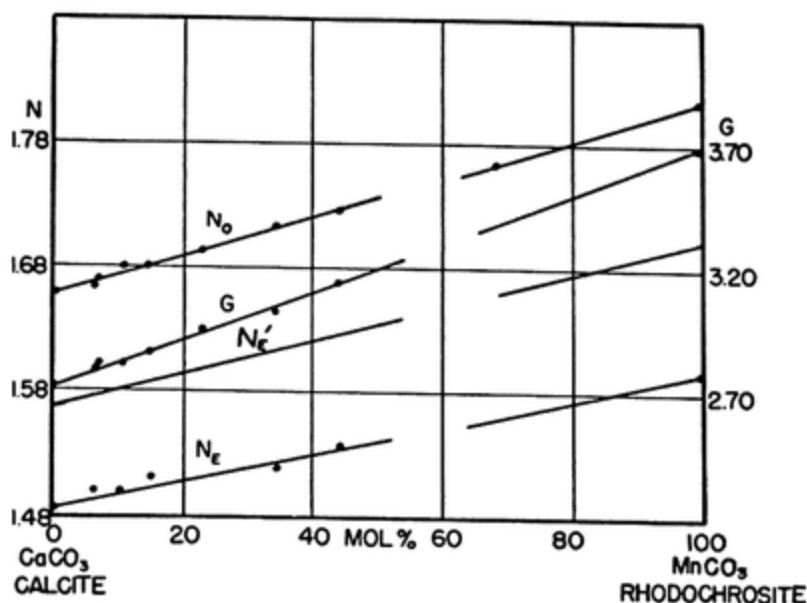
<sup>5</sup> P. Krieger: *Am. Mineral.*, XV, 23 (1930).

<sup>7</sup> Z. Harada: *Min. Abst.*, VI, 157 (1935).

<sup>8</sup> W. E. Ham and M. C. Oakes: *Econ. Geol.*, XXXIX, 425 (1944).

<sup>8a</sup> Calculated by Loupekine's method; see ref. 18.

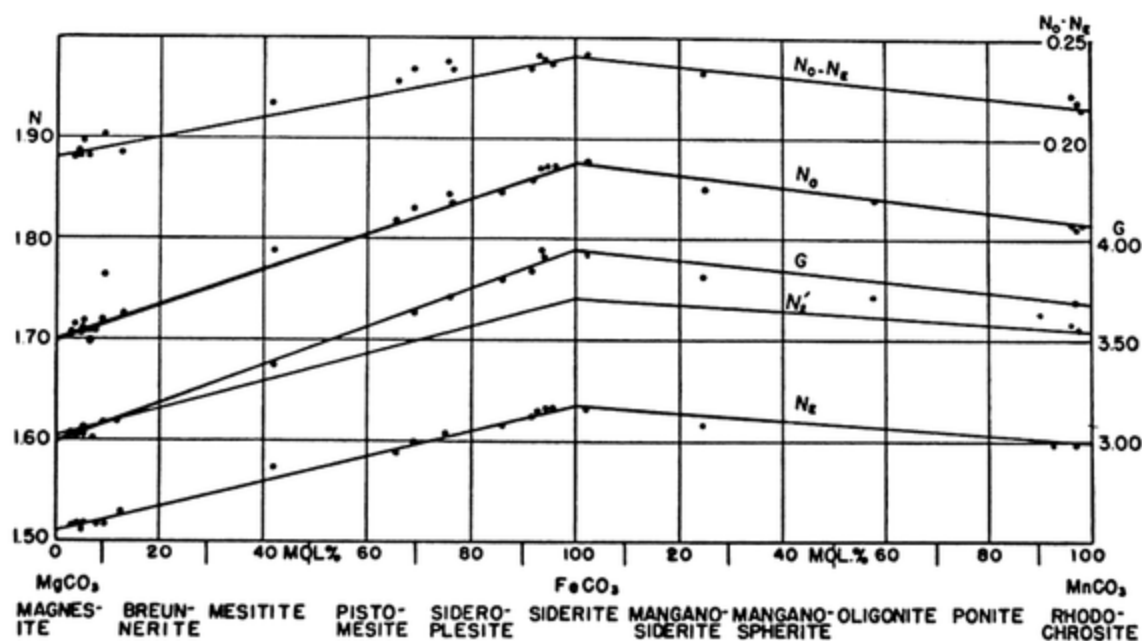
<sup>9</sup> R. E. Gibson, R. W. G. Wyckoff, and H. E. Merwin: *Am. Jour. Sci.*, CCX, 325 (1925).

FIG. 67. Properties of the  $\text{CaCO}_3$ - $\text{MnCO}_3$  (discontinuous?) series.

### BROWNSPAR HEXAGONAL SCALENOHEDRAL $(\text{Mg}, \text{Fe}, \text{Mn}, \text{Zn}, \text{Co})\text{CO}_3$

	$c/a$	Cleavage Angle	
Magnesite	0.8095	$72^\circ 30'$	$\text{MgCO}_3$
Siderite (Chalybite)	0.8184	$73^\circ 0'$	$\text{FeCO}_3$
Rhodochrosite	0.8259	$73^\circ 9'$	$\text{MnCO}_3$
Smithsonite	0.8063	$72^\circ 20'$	$\text{ZnCO}_3$
Spherochalcite	0.81		$\text{CoCO}_3$

COMP.  $\text{MgCO}_3$  and  $\text{FeCO}_3$  are miscible in all proportions, and  $\text{FeCO}_3$  and  $\text{MnCO}_3$  are also, but  $\text{MgCO}_3$  and  $\text{MnCO}_3$  have only limited miscibility. See Fig. 68.  $\text{MgCO}_3$ ,  $\text{ZnCO}_3$ ,  $\text{CoCO}_3$ , and probably also

FIG. 68. Properties of brownspar—the  $(\text{MgCO}_3$ - $\text{FeCO}_3$ - $\text{MnCO}_3$ ) double series.

FeCO<sub>3</sub><sup>10</sup> are completely miscible; minor amounts of CdCO<sub>3</sub>, CuCO<sub>3</sub>, and CaCO<sub>3</sub> may be present.

STRUC. Space group  $R\bar{3}c$ ;  $a$  for MgCO<sub>3</sub> 5.90 Å, for FeCO<sub>3</sub> 5.82, for MnCO<sub>3</sub> 5.84, for ZnCO<sub>3</sub> 5.62, for <sup>11</sup> CoCO<sub>3</sub> 5.72;  $\alpha_{rh}$  ca. 48°. U.C. 2.

PHYS. CHAR. Crystals commonly rhombohedral with perfect 10 $\bar{1}1$  cleavage; rhombohedral crystal faces often curved in siderite.  $H.$  = 3.5–4.5.  $G.$  = 2.96 (MgCO<sub>3</sub>), 3.89 (FeCO<sub>3</sub>), 3.7 (MnCO<sub>3</sub>), 4.4 (ZnCO<sub>3</sub>), 4.1 (CoCO<sub>3</sub>). Insoluble (MgCO<sub>3</sub>) to slowly soluble in cold HCl; soluble with effervescence in hot acid.  $F.$  = 7 (except in siderite,  $F.$  = 4.5, with decrepitation, becoming magnetic). MnCO<sub>3</sub> decrepitates and turns black before the blowpipe.

OPT. PROP. Uniaxial negative with extreme birefringence. Refrindex, birefringence, and birefringence-dispersion ratio vary much with varying composition, as follows (see also Figs. 69–72).

	Magne- site <sup>12</sup>	Brunnerite		Mesitite <sup>14</sup>	Pistome- site <sup>12</sup>	Sideroplesite <sup>12</sup>		Sider- ite <sup>12</sup>
MgCO <sub>3</sub> =	100.0	91.0 <sup>12</sup>	90.2 <sup>13</sup>	65.8	49.8	23.3	9.1	0.0
FeCO <sub>3</sub> =	0.0	9.0	8.6	16.3	50.2	73.2	83.6	100.0
N <sub>O</sub> =	1.700	1.707	1.719	1.719	1.788	1.830	1.847	1.875
N <sub>E</sub> =	1.509	1.517	1.517	1.527	1.570	1.596	1.613	1.633
N <sub>O</sub> - N <sub>E</sub> =	0.191	0.190	0.202	0.192	0.218	0.234	0.234	0.242
N <sub>E'</sub> on (10 $\bar{1}1$ ) =	1.602	1.607 <sup>8a</sup>	1.613 <sup>8a</sup>	1.619 <sup>8a</sup>	1.673 <sup>8a</sup>	1.707 <sup>8a</sup>	1.725 <sup>8a</sup>	1.747
B/D <sup>15</sup> =	24.5							18.6
G. =	2.98		3.09	3.12				3.95

	Siderite <sup>12,16</sup>		Mangano- siderite <sup>16</sup>	Mangano- spherite	Oligo- nite <sup>17</sup>	Ponite <sup>16</sup>	Rhodochrosite		Smith- sonite
FeCO <sub>3</sub> =	100.0	97.7	77.2		42.0	19.9	1.6	0.0	0.0
MnCO <sub>3</sub> =	0.0	1.8	15.8		57.0	79.3	97.8	100.0	0.0
N <sub>O</sub> =	1.875	1.8724	1.849		1.840	1.8279	1.816	1.816	1.850
N <sub>E</sub> =	1.633	1.6338	1.615			1.6057	1.600	1.597	1.625
N <sub>O</sub> - N <sub>E</sub> =	0.242	0.2386	0.234			0.2222	0.216	0.219	0.225
N <sub>E'</sub> on (10 $\bar{1}1$ ) =	1.748 <sup>18</sup>	1.747 <sup>8a</sup>	1.727 <sup>8a</sup>		1.695	1.712 <sup>8a</sup>	1.702 <sup>8a</sup>	1.702 <sup>18</sup>	1.732 <sup>18</sup>
B/D =	18.6							12.5	22.0
G. =	3.95	3.93			3.72		3.69	3.60	4.4

<sup>10</sup> A. Ferrari and C. Colla: *Min. Abst.*, VIII, 9 (1941).

<sup>11</sup> M. Baccaredda: *Min. Abst.*, V, 314 (1933).

<sup>12</sup> W. E. Ford: *Trans. Conn. Acad. Sci.*, XXII, 211 (1917).

<sup>13</sup> K. Schoklitsch: *Zeit. Krist.*, XC, 433 (1935), with 1.2 MnCO<sub>3</sub>.

<sup>14</sup> P. Gaubert: *Bull. Soc. Fr. Min.*, XLII, 88 (1919), with 12.8 MnCO<sub>3</sub> and 1.2 CaCO<sub>3</sub> (?).

<sup>15</sup>  $B/D = B_{Na}/(B_F - B_C)$  = birefringence for Na light divided by the birefringence dispersion or  $(B_F - B_C)$ . See A. N. Winchell and W. B. Meek: *Am. Mineral.*, XXXII, 336 (1947).

<sup>16</sup> R. G. Wayland: *Am. Mineral.*, XXVII, 614 (1942).

<sup>17</sup> E. B. Mayo and W. J. O'Leary: *Am. Mineral.*, XIX, 304 (1934).

<sup>18</sup> S. Loupekine: *Am. Mineral.*, XXXII, 502 (1947), gives a chart for determining N<sub>E</sub> from N<sub>O</sub> and N<sub>E'</sub> on cleavage grains.

Possible compositions and  $N_E$  can be obtained approximately from  $N_O$  or  $N_E'$  by the use of Fig. 75.

Siderite<sup>19</sup> with about 6% (Ca,Mg)CO<sub>3</sub> has  $N_O = 1.851$ ,  $N_E = 1.612$ ,  $N_O - N_E = 0.239$ .

Rhodochrosite<sup>20</sup> with 75.0 MnCO<sub>3</sub>, 12.7 FeCO<sub>3</sub>, 6.9 CaCO<sub>3</sub>, and 5.4 MgCO<sub>3</sub> has  $N_O = 1.790$ ,  $G. = 3.38$ ; with 74.7 MnCO<sub>3</sub>, 7.2 FeCO<sub>3</sub>, 11.8 CaCO<sub>3</sub>, and 6.3 MgCO<sub>3</sub>

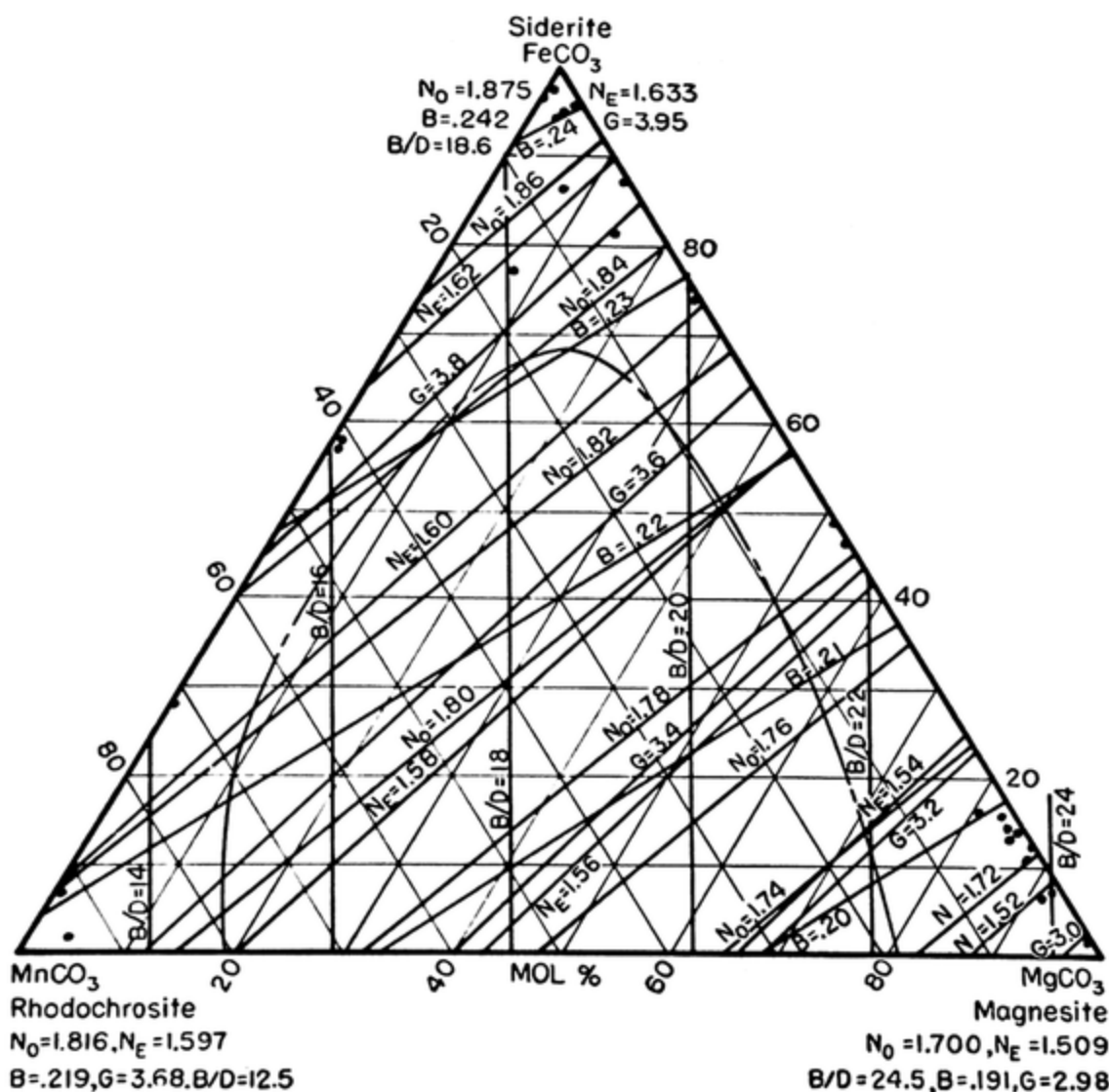


FIG. 69. Properties of the MgCO<sub>3</sub>-FeCO<sub>3</sub>-MnCO<sub>3</sub> ternary system. Each dot represents an analysis. The curved dash line indicates estimated limit of miscibility.

it has  $N_O = 1.795$ ,  $G. = 3.51$ ; with 53.8 MnCO<sub>3</sub>, 4.3 FeCO<sub>3</sub>, 37.5 CaCO<sub>3</sub>, and 4.4 MgCO<sub>3</sub> it has  $N_O = 1.731$ ,  $G. = 5.03$ .

Smithsonite<sup>21</sup> with 97.34 ZnCO<sub>3</sub> and 0.93 FeCO<sub>3</sub> has  $G. = 4.4$ ,  $N_O = 1.849$ ,  $N_E = 1.621$ ,  $N_O - N_E = 0.228$ ,  $F - C = 0.0168$  for  $N_O$  and 0.0085 for  $N_E$ ; with

<sup>19</sup> E. V. Shannon: *Proc. U. S. Nat. Mus.*, LXII, Art. 12 (1923).

<sup>20</sup> T. Yosimura: *Am. Mineral.*, XXIV, 660 (1939).

<sup>21</sup> E. D. Mountain: *Mineral. Mag.*, XXI, 51 (1926); A. Neuhaus: *Min. Abst.*, X, 92 (1947).

93.9  $ZnCO_3$  and 6.1  $CuCO_3$  it has  $N_O = 1.847$ ,  $G = 4.41$ ; with 90.4  $ZnCO_3$  and 3.5  $MnCO_3$  it has <sup>22</sup>  $N_O = 1.872$ ,  $N_E = 1.612$ ,  $N_O - N_E = 0.260$ . Smithsonite with about 50%  $FeCO_3$  has been called *monheimite*.

Spherochalcite has  $H = 4.5$ ,  $G = 4.1$ ,  $N_O = 1.855$ ,  $N_E = 1.600$ ,  $N_O - N_E = 0.255$ ;  $N_E'$  on  $(10\bar{1}1) = 1.722$ .<sup>18</sup>

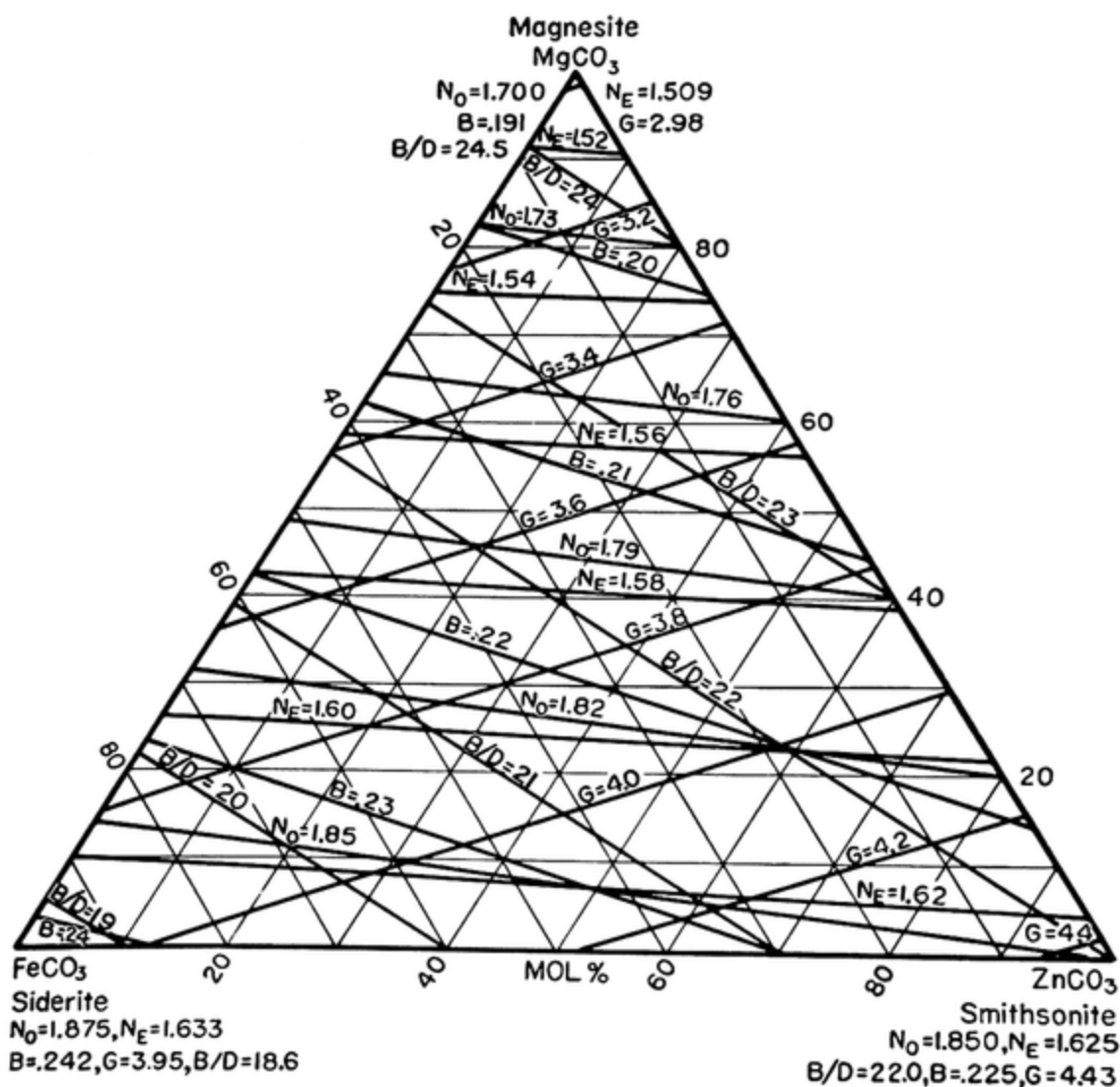


FIG. 70. Properties of the  $FeCO_3$ - $MgCO_3$ - $ZnCO_3$  system.

Magnesite is white, yellowish, grayish, brown; colorless in section.

Siderite is gray or, rarely, green; by alteration it becomes brown to red. In thin section it is ashen gray to colorless; absorption often visible with  $E < O$ .

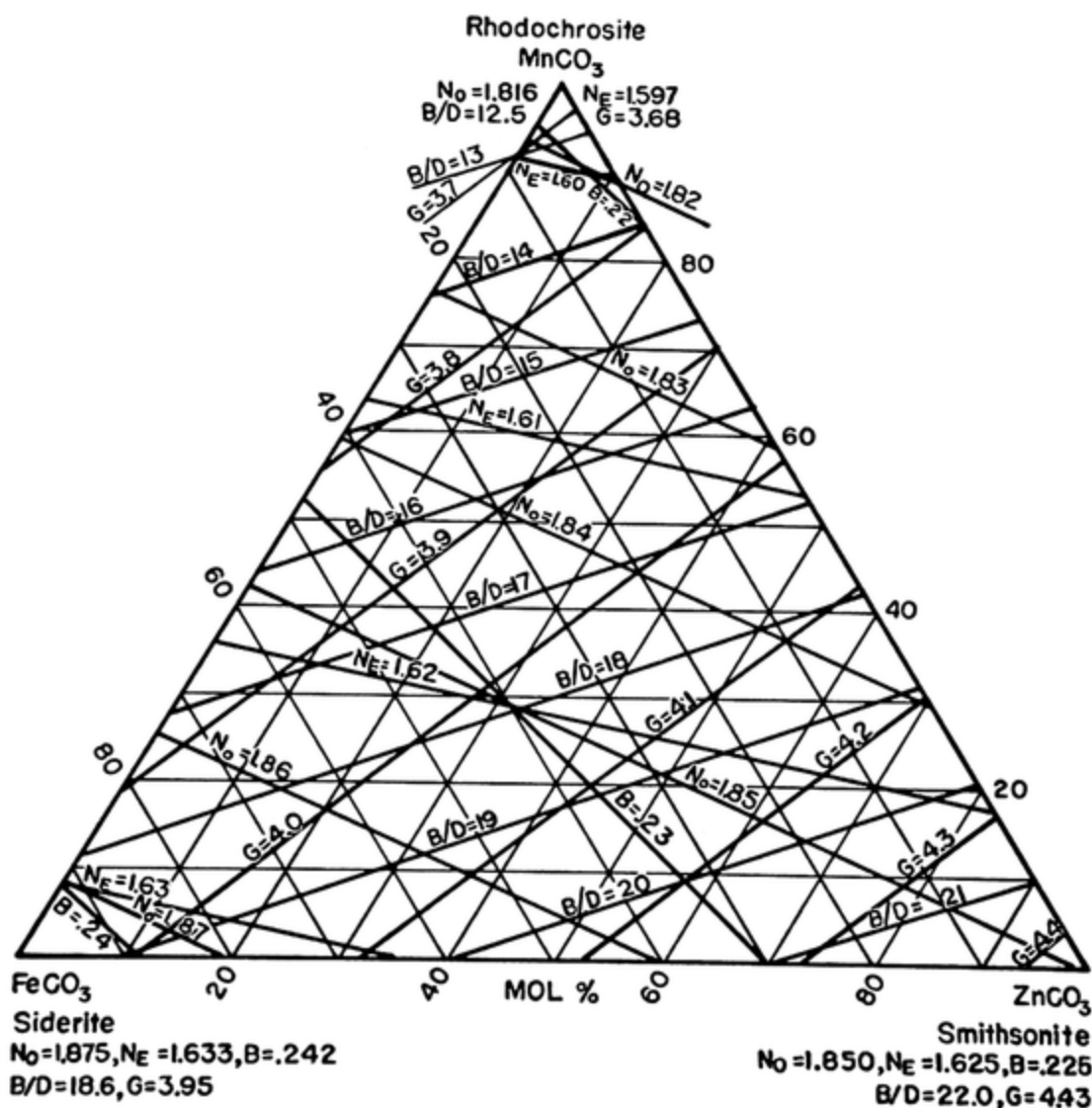
Rhodochrosite is rose-red, dark red, yellowish gray, brown; colorless in section.

Smithsonite is white, greenish, brownish, blue; colorless in section.

<sup>22</sup> P. Gaubert: *Bull. Soc. Fr. Min.*, XLII, 99 (1919).

Spherochalcite is rose-red or black; colorless in section.

**ALTER.** Magnesite alters very rarely and dissolves only slowly in cold acid. Chalybite changes very readily, on exposure, to limonite or hematite, or even magnetite. Rhodochrosite alters rather easily to pyrolusite. Smithsonite may change to calamine or, in part, to limonite.





DIAG. Magnesite is distinguished from calcite by absence of lamellar twinning and from calcite and magnesiadolomite by insolubility in cold dilute acid and by somewhat higher specific gravity and refractive indices. Siderite differs from calcite, magnesiadolomite, and magnesite in having both indices of refraction decidedly higher than that of Canada

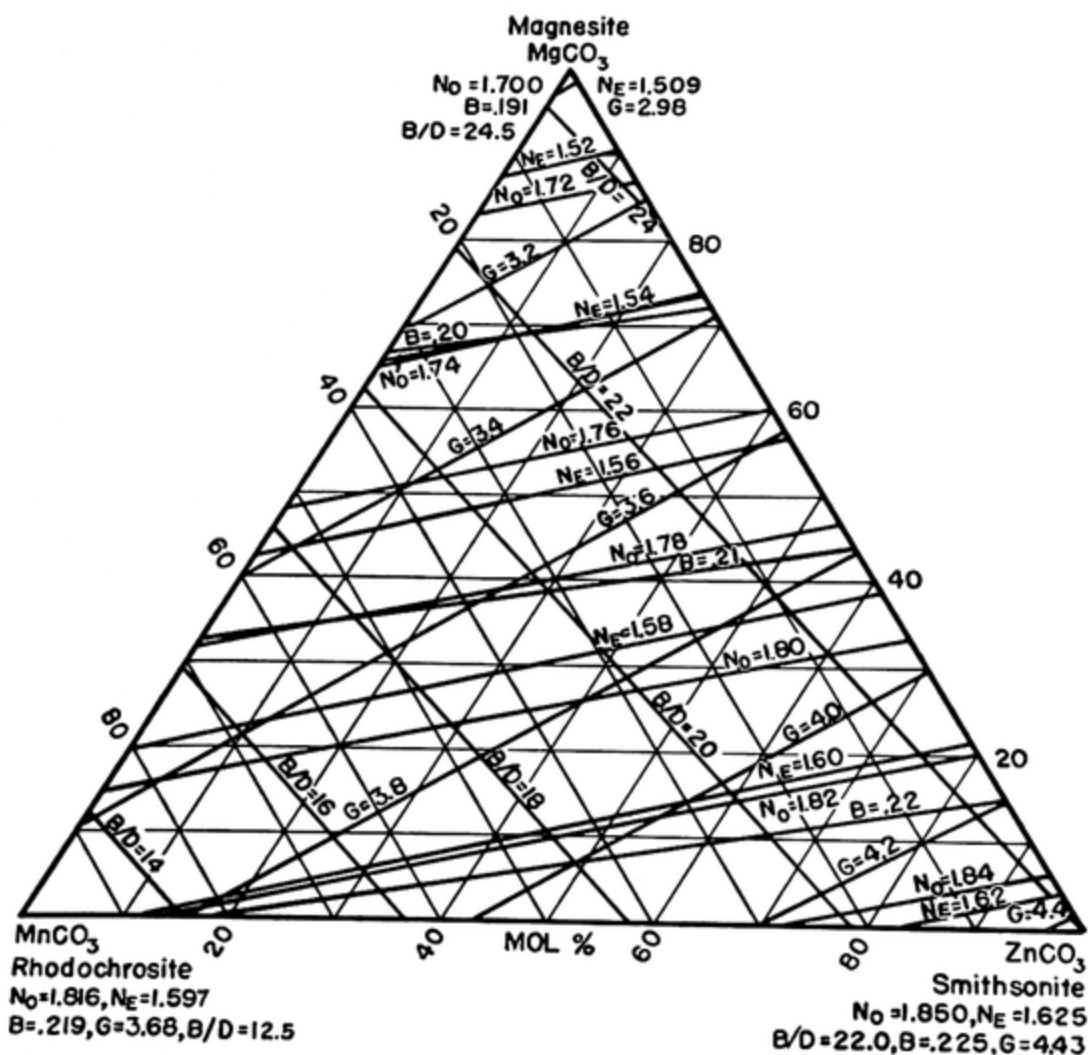


FIG. 72. Properties of the  $\text{MgCO}_3\text{-MnCO}_3\text{-ZnCO}_3$  system.

balsam; also in the common presence of limonite as an alteration product, and in having higher specific gravity. It differs from calcite and magnesiodolomite in its insolubility in cold dilute acid, and from magnesiodolomite and magnesite in the common presence of lamellar twinning. It also has an ashen gray color in thin section, with distinct absorption, which is especially characteristic, though not prominent. Rhodochrosite differs from other types of brownspars in the usual pink color, in giving tests for abundant manganese, in its associated minerals, and in its common alteration to pyrolusite. Spherochalcite is quite rare.

**OLomite****RHOMBOHEDRAL**

$c/a = 0.80-0.83$

**COMP.** Common dolomite or *magnesiadolomite* is nearly pure  $\text{CaMg}(\text{CO}_3)_2$ ; this is miscible in all(?) proportions with  $\text{CaFe}(\text{CO}_3)_2$  or *ferrodolomite*, and also probably with  $\text{CaMn}(\text{CO}_3)_2$  or *mangadolomite*; limited amounts of  $\text{CaCa}(\text{CO}_3)_2$  or  $\text{MgMg}(\text{CO}_3)_2$  seem to enter dolomite crystals occasionally. Rarely, a little Co or Zn may be present. Types intermediate between magnesiadolomite and ferrodolomite are known as *parankerite* (with Mg:Fe about 2:1) and *ankerite* (with Mg:Fe about 1:1).

**STRUC.** Space group  $R\bar{3}$ ;  $a$  6.0–6.1 Å. U.C. 1.

**PHYS. CHAR.** Crystals commonly rhombohedral in habit; rhombohedral faces often curved; crystal forms common even in massive rocks. Twinning on 0001 or  $10\bar{1}1$ . Perfect  $10\bar{1}1$  cleavage.  $H. = 3.5-4$ .  $G. = 2.87$ .  $F. = 7$ . Only slowly soluble (with effervescence) in cold dilute acid.

**OPT. PROP.** Uniaxial negative with extreme birefringence. The refringence and birefringence increase with increase of iron or manganese, as shown in Figs. 73, 74 and in the following data:

COMPOSITION <sup>23</sup>			C 656	D 589	F 486	F – C
$\text{MgCO}_3$	50.7		$N_O = 1.6754$	1.6799	1.6893	0.0139
$\text{CaCO}_3$	49.2		$N_E = 1.4993$	1.5013	1.5054	0.0061
$\text{FeCO}_3$	0.1		$N_O - N_E = 0.1761$	0.1786	0.1839	0.0078

	Magnesiadolomite		Parankerite	Ankerite		Ferrodolomite	Mangadolomite
$\text{CaMg}(\text{CO}_3)_2$	100.0 <sup>12</sup>	90.0 <sup>24</sup>	80.0 <sup>24</sup>	52.4 <sup>13</sup>	24.7 <sup>12</sup>	0.0 <sup>25</sup>	0.0 <sup>12</sup>
$\text{CaFe}(\text{CO}_3)_2$	0.0	8.0	20.0	45.6	70.6	100.0	0.0
$\text{CaMn}(\text{CO}_3)_2$	0.0	0.0	0.0	2.0	4.6	0.0	100.0
$N_O =$	1.679	1.686	1.698	1.728	1.741	1.765	1.743
$N_E =$	1.502	1.505	1.513	1.531	1.536	1.555 ca.	1.546
$N_O - N_E =$	0.177	0.181	0.187	0.197	0.205	0.210 ca.	0.197
$N_E'$ on $(10\bar{1}1) =$	1.587 <sup>18</sup>	1.591 <sup>8a</sup>	1.601 <sup>8a</sup>	1.625 <sup>8a</sup>	1.633 <sup>8a</sup>	1.655 ca.	1.64 ca.
$G. =$	2.87	2.94	?	3.02	3.12	3.2 ca.	3.1 ca.

$N_E$  can be obtained approximately from  $N_O$  or  $N_E'$  by the use of Fig. 75.

Color white, reddish, greenish, pink, brown, gray, black. Colorless in thin section.

**OCCUR.** Magnesiadolomite is the chief constituent of the rock known as dolomite and of dolomite-marble; it is common in some limestones

<sup>23</sup> P. Koller: *N. Jahrb. Min.*, Bl. Bd. XLII, 457 (1919):  $G. = 2.882$ .

<sup>24</sup> K. Eisenhut: *Zeit. Kryst.*, XXXV, 607 (1902).

<sup>25</sup> L. Hawkes and J. A. Smythe: *Mineral. Mag.*, XXIV, 65 (1935); J. A. Smythe and K. C. Dunham: *Mineral. Mag.*, XXVIII, 53 (1947).

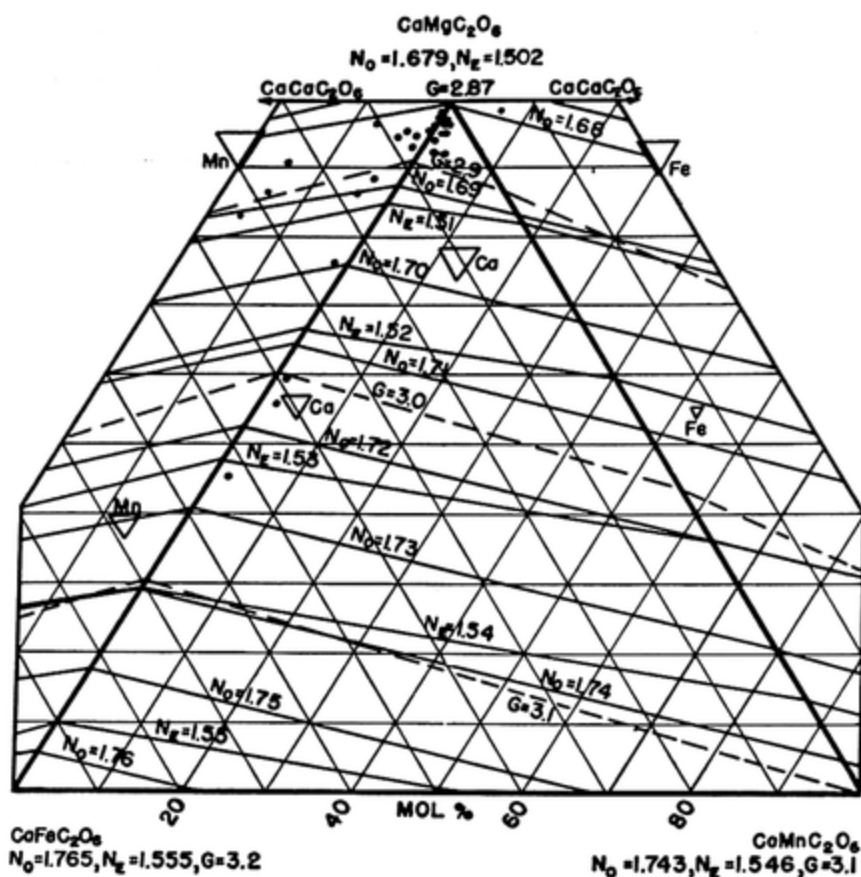


FIG. 73. Properties of the dolomite system. Each dot represents an analysis.

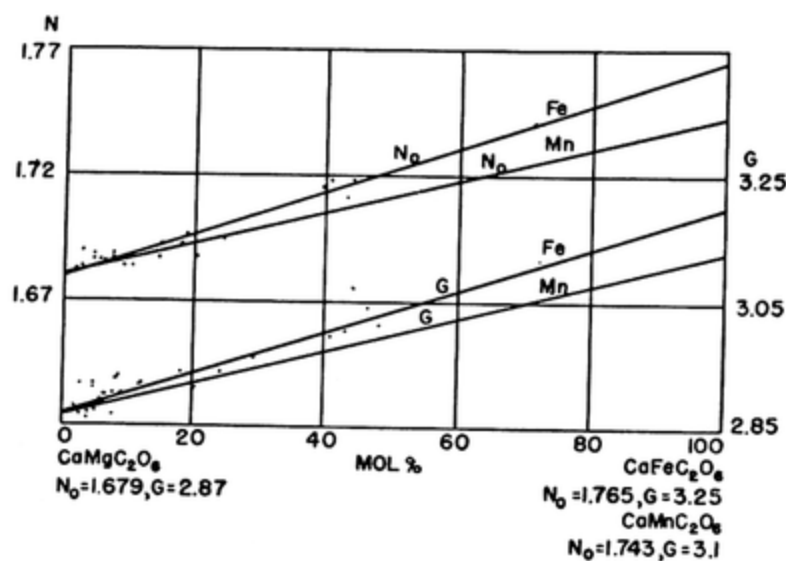


FIG. 74. Properties of the  $\text{CaMg}(\text{CO}_3)_2$ - $\text{Ca}(\text{Fe,Mn})(\text{CO}_3)_2$  double series.

and not rare as a secondary mineral in igneous and other rocks. X-ray analysis of the residue left after evaporation of centrifuged Lake Mendota water, which contains the constituents of magnesioidolomite in cor-

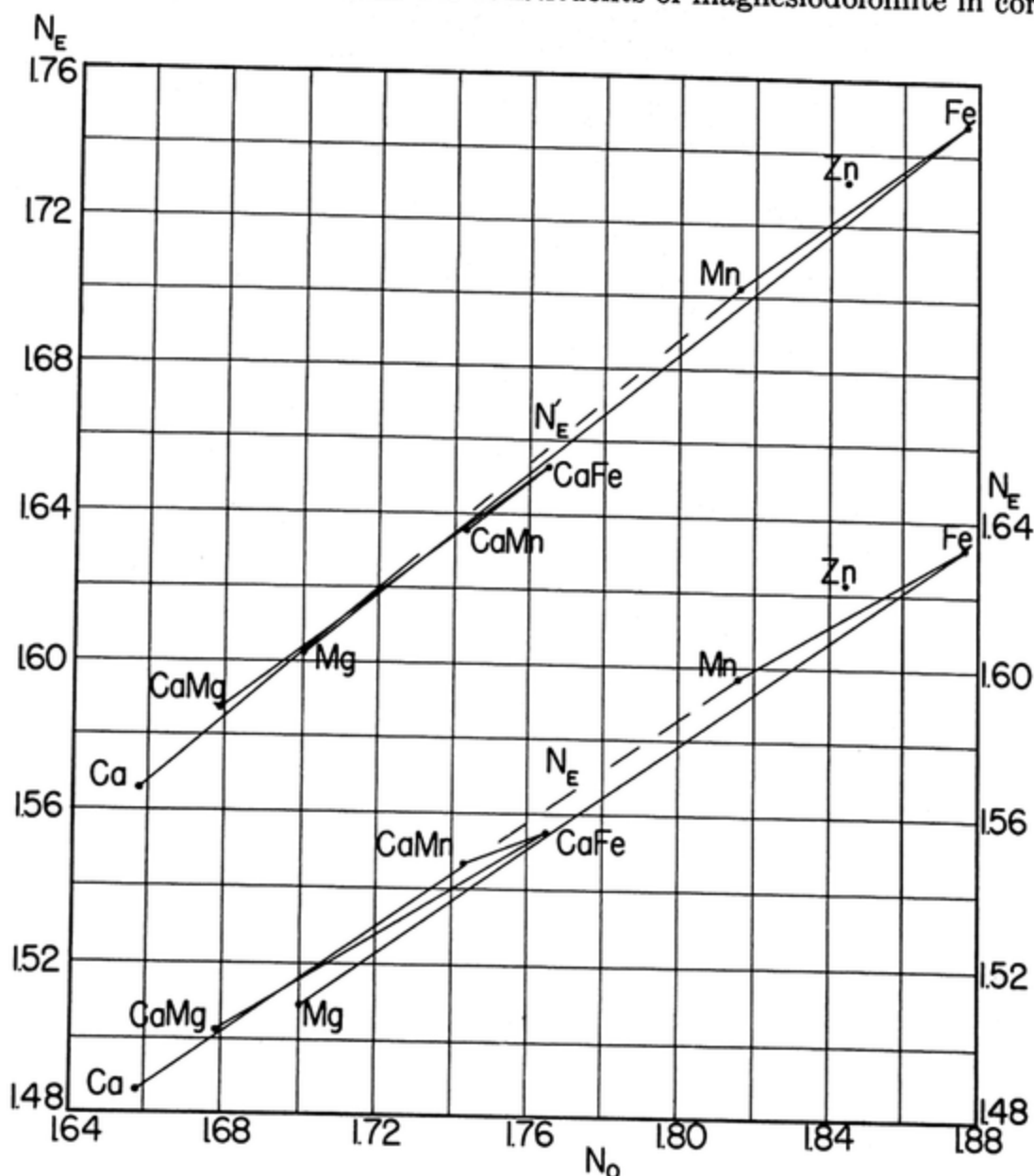


FIG. 75. Relations between  $N_0$ ,  $N_E$ , and  $N_E'$  and the composition in rhombohedral carbonates.

rect proportions, does not disclose that mineral, but, instead, abundant aragonite, little calcite, and strictly amorphous material. Ferrodolomite, ankerite, and mangandolomite are found uncommonly in veins, etc.

DIAG. Magnesioidolomite and ankerite are distinguished from calcite by tendency to show crystal outlines, the usual absence of lamellar twinning, only slow solubility in cold dilute acids, and higher specific gravity.

## ARAGONITE GROUP

The minerals of the aragonite group are carbonates of divalent bases having orthorhombic symmetry. The crystals often show twinning on 110 to pseudohexagonal forms. The minerals all have cleavages parallel to 010 and 110, and a hardness of 3 to 4; their optic properties are similar, all having the acute negative bisectrix of a small optic angle parallel to  $c$ . The minerals of the group are:

Aragonite	$a:b:c = 0.6228:1:0.7204$	$CaCO_3$
Strontianite	$a:b:c = 0.6090:1:0.7237$	$SrCO_3$
Cerussite	$a:b:c = 0.6102:1:0.7232$	$PbCO_3$
Witherite	$a:b:c = 0.5949:1:0.7413$	$BaCO_3$
Alstonite	$a:b:c = 0.583:1:0.719$	$CaBa(CO_3)_2$

These compounds have only limited miscibility in crystals as illustrated by the double salt, alstonite.

## ARAGONITE

## ORTHORHOMBIC DIPYRAMIDAL

 $CaCO_3$ 

$$a:b:c = 0.6228:1:0.7204$$

STRUC. Space group  $Pmcn$ ;  $a$  4.94,  $b$  7.94,  $c$  5.72 Å. U.C. 4.

PHYS. CHAR. Crystals commonly acicular to prismatic with domes or pyramids. Twinning on 110 often gives pseudohexagonal groups which can be distinguished from true hexagonal crystals by the re-entrant angles in the prism zone and by striations on the base. See Figs. 76 and 77. Imperfect 010 and 110 cleavages, rarely seen in thin section because the mineral is often in fibrous or acicular aggregates.  $H. = 3.5-4$ .  $G. = 2.94$ .  $F. = 7$ , but falls to a white powder on account of dissociation to  $CaO$  and  $CO_2$ , complete at  $900^\circ C$ . Fusible at  $1290^\circ C$ . under a pressure of 110 atmospheres of  $CO_2$ . Readily soluble in cold dilute acid with effervescence.

OPT. PROP. The negative acute bisectrix  $X$  is normal to the base, and the optic plane is parallel with 100. See Fig. 78. The refringence is visibly different in most sections, ranging from low to high. The birefringence is extreme, producing iridescent colors, due to slight variations in thickness, similar to those of calcite. The elongation is negative.

$(- )2V = 18^\circ 11'$  ( $2E = 30^\circ 52'$  Na),  $r < v$  weak.  $N_X = 1.530$ ,  $N_Y = 1.681$ ,  $N_Z = 1.685$ ,  $N_Z - N_X = 0.155$ ;  $F - C$  for  $N_Y = 0.0128$ .

Aragonite <sup>26</sup> with 3.12%  $PbCO_3$  has  $G. = 3.01-3.02$ ,  $N_X = 1.5424$ ,  $N_Y = 1.6945$ ,  $N_Z = 1.6994$ ,  $N_Z - N_X = 0.157$ . Aragonite <sup>27</sup> with 5.5%  $SrCO_3$  has  $N_X = 1.527$ ,

<sup>26</sup> W. Siegl: *Min. Abst.*, VI, 529 (1937).

<sup>27</sup> C. O. Hutton: *Min. Abst.*, VI, 364 (1936).

$N_Y = ?$ ,  $N_Z = 1.676$ ,  $N_Z - N_X = 0.149$ . Aragonite with  $\approx 4.53$  PbO has  $(- )2V = 23^\circ$ ,  $N_X = 1.5397$ ,  $N_Y = 1.6950$ ,  $N_Z = 1.7026$ ,  $N_Z - N_X = 0.163$  (for  $\lambda = 577$ );  $G. = 3.02$ .

Colorless, white, or stained. Colorless in section.

INVER. Aragonite, alone or with calcite, is obtained by precipitation from aqueous solution at ordinary temperatures. It inverts to calcite in a few days at  $100^\circ \text{C.}$ , and more rapidly at higher temperature.



FIG. 76. Aragonite twinned on  $110$ .

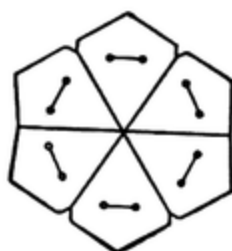


FIG. 77. Cross section of a pseudohexagonal twin of aragonite.

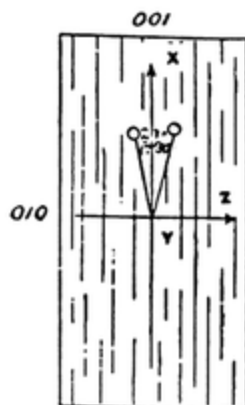


FIG. 78. The optic orientation of aragonite.

OCCUR. Many shells are composed of aragonite, which is not rare in lake deposits, ore deposits, and various rocks, especially as an alteration product.

DIAG. Aragonite differs from calcite in its biaxial character and poorer cleavages; in fibrous forms the cleavages in aragonite are parallel to the elongation, while in calcite they are oblique. Aragonite differs from witherite, strontianite, and cerussite in the position of the optic plane.

## STRONTIANITE

ORTHORHOMBIC DIPYRAMIDAL

$\text{SrCO}_3$

$$a:b:c = 0.6090:1:0.7237$$

STRUC. Space group  $Pmcn$ ;  $a$  5.13,  $b$  8.42,  $c$  6.10 Å. U.C. 4.

PHYS. CHAR. Crystals commonly acicular; twinning on  $110$  common both in lamellar and pseudohexagonal groups. Distinct  $110$  cleavages.  $H. = 3.5-4$ .  $G. = 3.71$ .  $F. = 1497^\circ \text{C.}$ <sup>29</sup> after swelling and sprouting. Soluble in  $\text{HCl}$  with effervescence.

OPT. PROP. The negative acute bisectrix  $X$  is normal to  $001$ ; the optic plane is parallel with  $010$ . See Fig. 79.  $(- )2V = 7^\circ$  ( $2E = 12^\circ 17'$

<sup>28</sup> H. O'Daniel: *Zeit. Krist.*, LXXIV, 333 (1930).

<sup>29</sup> H. E. Boeke: *N. Jahrb. Min.*, I, 9 (1914).



$N_a$ ),  $r < v$  very weak.  $N_X = 1.516$ ,  $N_Y = 1.664$ ,  $N_Z = 1.666$ ,  $N_Z - N_X = 0.150$ .

Color pale to apple green, white, yellow. Colorless in section.

INVER. A reversible inversion at  $929^\circ \text{C.}$  to a hexagonal form, which fuses at  $1497^\circ \text{C.}$

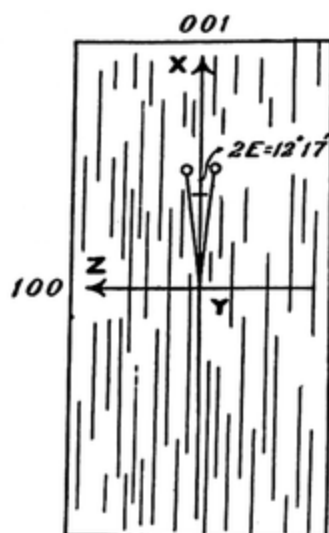


FIG. 79. The optic orientation of strontianite.

OCCUR. Strontianite is found in veins and geodes, and in concretions in limestone, etc.; thus at Strontian, England; Braunsdorf, Saxony; Clinton, New York; etc.

DIAG. Strontianite differs from aragonite in having distinct cleavages, a higher density, and a different position of the optic plane.

## CERUSSITE

ORTHORHOMBIC DIPYRAMIDAL

$\text{PbCO}_3$

$a:b:c = 0.6102:1:0.7232$

STRUC. Space group  $Pmcn$ ;  $a$  5.16,  $b$  8.47,  $c$  6.15 Å. U.C. 4.

PHYS. CHAR. Crystals {010} tablets, brachydomatic, or pyramidal. Twinning on 110 common; on 130 less common. Distinct 110 and 021 cleavages.  $H. = 3-3.5$ .  $G. = 6.57$ .  $F. = 1.5$ . Soluble in dilute  $\text{HNO}_3$  with effervescence.

OPT. PROP. The negative acute bisectrix  $X$  is normal to 001; the optic plane is parallel with 010. See Fig. 80. With lowering temperature the optic angle decreases, becoming uniaxial at  $-119^\circ \text{C.}$  and biaxial with  $2E = 11^\circ$  in 100 at  $-190^\circ \text{C.}$   $(-)2V = 8^\circ 34'$

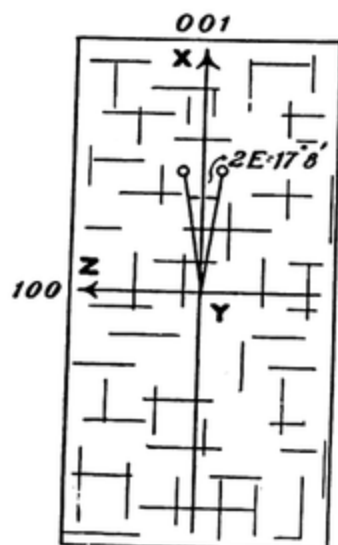


FIG. 80. The optic orientation of cerussite.

Na,<sup>30</sup>  $r > v$  marked (uniaxial<sup>31</sup> at 15° C. for 415 mμ).  $N_X = 1.803$ ,  $N_Y = 2.074$ ,  $N_Z = 2.076$ ,  $N_Z - N_X = 0.273$ .

Color white, gray, grayish black. Colorless in section.

OCCUR. Cerussite is found chiefly in the oxide zone of lead ore deposits.

DIAG. Cerussite differs from anglesite in having extreme birefringence; it differs from aragonite, witherite, and strontianite in very high relief and extreme birefringence.

## WITHERITE

ORTHORHOMBIC DIPYRAMIDAL

BaCO<sub>3</sub>

$a:b:c = 0.5949:1:0.7314$

STRUC. Space group *Pmcn*;  $a$  5.28,  $b$  8.83,  $c$  6.39 Å. U.C. 4.

PHYS. CHAR. Crystals pseudohexagonal pyramids by twinning on 110. Distinct 010 and poor 110 and 012 cleavages.  $H. = 3.5$ .  $G. = 4.3$ .  $F. = 2.5-3$ , giving yellowish green flame color. Under sufficient pressure of CO<sub>2</sub>, BaCO<sub>3</sub> fuses<sup>29</sup> at 1740° C. Soluble in dilute HCl with effervescence.

OPT. PROP. The optic plane is parallel with 010 and the negative acute bisectrix  $X$  is normal to 001.  $(- )2V = 16^\circ$ ,  $r > v$  very weak.  $N_X = 1.529$ ,  $N_Y = 1.676$ ,  $N_Z = 1.677$ ,  $N_Z - N_X = 0.148$ .

Color white, yellowish, grayish. Colorless in section.

INVER. Witherite inverts<sup>29</sup> at 811° C. to a hexagonal form, which inverts at 982° C. to an isometric form, which fuses at about 1740° C.

OCCUR. Witherite is usually associated with ores in veins, as at Lexington, Kentucky.

DIAG. Witherite is distinguished by high density and yellowish green flame color.

**Alstonite** [CaBa(CO<sub>3</sub>)<sub>2</sub>] or *bromlite* is a double salt which is orthorhombic with  $a:b:c = 0.583:1:0.719$ ;  $a$ <sup>32</sup> 4.99,  $b$  8.77,  $c$  6.11. U.C. 2. Crystals pseudohexagonal pyramids. It may contain 5-10% of SrCO<sub>3</sub>.  $G. = 3.71$ . A sample<sup>33</sup> with CaO = 17.6, BaO = 48.54, SrO = 4.25, CO<sub>2</sub> = 29.41, has  $(- )2V = 7^\circ 14'$ ,  $N_X = 1.5261$ ,  $N_Y = 1.6710$ ,  $N_Z = 1.6717$ ,  $N_Z - N_X = 0.1456$ . Found in lead deposits, as near Alston, England.

**Nesquehonite** (MgCO<sub>3</sub>·3H<sub>2</sub>O) is said to be orthorhombic dipyramidal<sup>34</sup> with  $a:b:c = 0.644:1:0.452$ . Space group *Pmmm*;  $a$  7.68,  $b$  11.93,  $c$  5.39 Å. U.C. 4. Crystals long prismatic, vertically striated, with perfect 110 and poor 001 cleavages.  $H. = 2.5$ .  $G. = 1.85$ . Soluble in cold HCl with effervescence. The optic plane is

<sup>30</sup> H. Dübigk: *N. Jahrb. Min.*, Bl. Bd. XXXVI, 214 (1913).

<sup>31</sup> P. Sève: *Bull. Soc. Fr. Min.*, XLIII, 9 (1920).

<sup>32</sup> B. Gossner and F. Mussnug: *Cent. Min. Geol. Pal.*, 1930A, 220.

<sup>33</sup> S. Kreutz: *N. Jahrb. Min.*, II, 12 (1910).

<sup>34</sup> M. Fenoglio: *Per. Min. Roma*, IV, 443 (1933), VI, 1 (1935); and *Atti. Accad. Lincei*, XXIV, 219 (1936).

001;  $X = a$ . The optic axes are nearly normal to the 110 cleavages.  $(- )2V = 53^\circ (2E = 83^\circ 20' \text{ Li}, 84^\circ 19' \text{ Na})$ .  $N_X = 1.417$ ,  $N_Y = 1.503$ ,  $N_Z = 1.527$ ,  $N_Z - N_X = 0.110$ . Colorless. Found in coal mines and also in serpentine.

**Lansfordite** ( $MgCO_3 \cdot 5H_2O$ ) is monoclinic prismatic<sup>34</sup> with  $a:b:c = 1.652:1:0.968$ ,  $\beta = 101^\circ 49'$ .  $a$  12.48,  $b$  7.55,  $c$  7.34 Å. U.C. 4. Crystals stalactitic with distinct 001 cleavage.  $H. = 2.5$ .  $G. = 1.73$ .  $F. = 7$ . Soluble in acid with effervescence. The optic plane and  $X$  are normal to 010;  $Z \wedge c = \text{small}$ .  $(+)2V = 60^\circ 37'$ ,  $N_X = 1.456$ ,  $N_Y = 1.476$ ,  $N_Z = 1.502$ ,  $N_Z - N_X = 0.046 \text{ Na}$ ; again:  $(+)2V = 59^\circ 48'$ ,  $N_X = 1.456$ ,  $N_Y = 1.469$ ,  $N_Z = 1.508$ ,  $N_Z - N_X = 0.052 \text{ Na}$ . Alters promptly in air to nesquehonite. Found as stalactites in a coal mine at Lansford, Pennsylvania.

**Barytocalcite** [ $CaBa(CO_3)_2$ ] is monoclinic prismatic<sup>35</sup> with  $a:b:c = 1.561:1:1.260$ ,  $\beta = 96^\circ 8'$ ; space group  $P2_1/m$ ;  $a$  8.15,  $b$  5.22,  $c$  6.58 Å. U.C. 2. Crystals elongated in a diagonal direction by extension of  $\{\bar{1}21\}$  and  $\{\bar{1}51\}$ ;  $\{100\}$  faces vertically striated. Perfect 110 and imperfect 001 cleavages. The three cleavages make a pseudorhombohedral nearly like that of calcite.  $H. = 4$ .  $G. = 3.65$ .  $F. = \text{difficult}$ . Soluble in dilute HCl with effervescence. The optic plane and  $Z$  are normal to 010;  $X \wedge c = -64^\circ 22'$ .  $(-)2V = 15^\circ$ ,  $r > v$  weak.  $N_X = 1.525$ ,  $N_Y = 1.684$ ,  $N_Z = 1.686$ ,  $N_Z - N_X = 0.161 \text{ Na}$ .<sup>36</sup> Color white, gray, greenish, yellowish. Found in limestone with barite and fluorite as at Alston-Moor, England.

## (b) WITH ADDITIONAL ANIONS—ANHYDROUS

**Bastnäsite** [(Ce,La,Di)FCO<sub>3</sub>] is hexagonal<sup>37</sup> (ditrigonal dipyramidal) with  $c/a = 1.371$ ; space group  $H\bar{6}c2$ ;  $a$  7.09,  $c$  9.72 Å. U.C. 6. Crystals prismatic with basal cleavage.  $H. = 4.5$ .  $G. = 4.89-4.99$ .  $F. = 7$ . Difficultly soluble in  $H_2SO_4$  with effervescence. Uniaxial positive with  $N_O = 1.717$ ,  $N_E = 1.818$ ,  $N_E - N_O = 0.101$  (Larsen);  $N_O = 1.722$ ,  $N_E = 1.824$ ,  $N_E - N_O = 0.102$  (Geijer<sup>38</sup>). Color yellow or reddish; in section brown with weak pleochroism. A similar mineral called *beixinite* from China.<sup>39</sup> gave:  $G. = 4.83$ ,  $N_O = 1.7169$ ,  $N_E = 1.791$ ,  $N_E - N_O = 0.0741$ . Found in veins, as at the Bastnäs mine in Sweden and Mountain Pass, California. Distinguished from xenotime after heating to redness for one minute, by yellow to yellow-brown color, reduced birefringence, and indices higher than 1.80.<sup>40</sup>

**Cordylite** [2(Ce,La,Di)FCO<sub>3</sub>·BaCO<sub>3</sub>] is hexagonal<sup>41</sup> with  $c/a = 5.25$ . Space group  $C6/mmc$ ;  $a$  7.56,  $c$  22.8 Å. Hexagonal U.C. 6. Crystals prismatic with distinct basal cleavage.  $H. = 4.5$ .  $G. = 4.31$ .  $F. = 7$ , but decrepitates and turns brown. Soluble in HCl with effervescence. Uniaxial negative with  $N_O = 1.760$ ,  $N_E = 1.577$ ,  $N_O - N_E = 0.183$ . May be zoned in vertical sections. Colorless or wax yellow with  $O = \text{greenish yellow}$ ,  $E = \text{brownish yellow}$ . Found in pegmatite in Greenland.

<sup>35</sup> B. Gossner and F. Muschnug: *Cent. Min.*, 1930A, 321.

<sup>36</sup> E. Mallard: *Bull. Soc. Fr. Min.*, XVIII, 7 (1895).

<sup>37</sup> I. Oftedal: *Zeit. Krist.*, LXXII, 239 (1929); LXXVIII, 462 (1931).

<sup>38</sup> P. Geijer: *Sver. Geol. Unders. Aarsb.*, 14, No. 6 (1921).

<sup>39</sup> T. L. Ho: *Bull. Geol. Soc. China*, XIV, 2, 279 (1935); *Min. Abst.*, VI, 151 (1937).

<sup>40</sup> W. R. Foster, *Amer. Mineral.*, 34, 830 (1949).

<sup>41</sup> I. Oftedal: *Zeit. Krist.*, LXXIX, 437 (1931).

**Synchysite** <sup>42</sup> [(Ce,La,Di)FCO<sub>3</sub>] is hexagonal with  $c/a = 3.365$ . Crystals acute rhombohedral,<sup>43</sup> often twinned on 0001. No cleavage.  $H. = 4.5$ .  $G. = 3.9$ .  $F. = 7$ . Uniaxial positive with  $N_O = 1.674$ ,  $N_E = 1.770$ ,  $N_E - N_O = 0.096$ . A similar mineral from Switzerland <sup>44</sup> gave:  $G. = 3.94+$ ,  $N_O = 1.649$ ,  $N_E > 1.74$ ,  $N_E - N_O = 0.091+$ . Color yellow, gray, or brown. May be weakly pleochroic with  $O =$  clear yellowish brown,  $E =$  pale greenish yellow-brown. Found in pegmatite, as in Sweden and Switzerland.

**Parisite** [2(Ce,La,Di)FCO<sub>3</sub>·CaCO<sub>3</sub>] is hexagonal <sup>41</sup> with  $c/a = 3.94$ ; space group  $C6/mmc$ ;  $a$  7.09,  $c$  27.93 Å. Hexagonal U.C. 6. Crystals barrel-shaped, horizontally striated, with perfect basal cleavage developed by alteration.  $H. = 4.5$ .  $G. = 4.42$ .  $F. = 7$ . Soluble in HCl with effervescence. Uniaxial positive with  $N_O = 1.672$ ,  $N_E = 1.771$ ,  $N_E - N_O = 0.099$ . Colorless in thin section; thick plates may be yellow with  $O =$  light yellow,  $E =$  golden yellow. It may show brown pigment in zones. Found in pegmatite, as in Montana and Siberia.

**Yttroparisite** <sup>45</sup> is very similar but contains much Y<sub>2</sub>O<sub>3</sub>. It is hexagonal with  $c/a = 1.115$ .  $a$  4.01,  $c$  4.47 Å. Uniaxial positive with  $N_O = 1.643$ ,  $N_E = 1.755$ ,  $N_E - N_O = 0.112$ . Found as inclusions in fluorite.

**Rutherfordite** (UO<sub>2</sub>CO<sub>3</sub>) is orthorhombic(?); finely fibrous. Soft.  $G. = 4.82$ . Soluble in acid with effervescence. Optic sign unknown.  $N_X = 1.72$ ,  $N_Y = 1.75$  ca.,  $N_Z = 1.80$  ca.,  $N_Z - N_X = 0.08$ . Color yellow. Earthy. An alteration product of uraninite.

## (b) WITH ADDITIONAL ANIONS—HYDROUS

**Ancylite** <sup>42</sup> [Sr<sub>3</sub>Ce<sub>4</sub>(OH)<sub>4</sub>(CO<sub>3</sub>)<sub>7</sub>·3H<sub>2</sub>O?] is orthorhombic with  $a:b:c = 0.916:1:0.917$ . May contain some La, Di, Ca, Fe, Mn. Crystals pyramidal without cleavage.  $H. = 4.5$ .  $G. = 3.95$ .  $F. = 7$ . Soluble in acid with effervescence.  $Y = c$ ;  $Z = b$ . Birefringence strong. Gordon <sup>46</sup> reports  $a:b:c = 0.571:1:0.534$  and  $X = a$ ,  $Y = b$ ,  $Z = c$ ;  $(- )2V = 66^\circ$  calc.,  $N_X = 1.625$ ,  $N_Y = 1.700$ ,  $N_Z = 1.735$ ,  $N_Z - N_X = 0.110$ . With 4.36 CaO, Fersman <sup>47</sup> finds  $G. = 3.82$ . Color brown, greenish, orange. Pale green in thin section. May contain inclusions of acmite. Found with albite in Greenland.

**Ambatoarinite** <sup>48</sup> [5SrO·5(Ce,La,Di)<sub>2</sub>O<sub>3</sub>·17CO<sub>2</sub>?] is perhaps the same as ancylite; it is orthorhombic with a prism angle of  $95^\circ$ . Soluble in cold HCl.  $X = c$ ;  $Y = b$ .  $(- )2V = ?$ ,  $N_X > 1.658$ ,  $N_Z - N_X = 0.08$ . Color black or red from impurities. A pneumatolytic product with celestite and monazite in Madagascar.

<sup>42</sup> G. Flink: *Bull. Geol. Inst. Upsala*, V, 81 (1901); *Medal. Grönland*, XXIV, 29 (1901).

<sup>43</sup> Synchysite is described by I. Oftedal in *Zeit. Krist.*, LXXIX, 437 (1931), as dihexagonal dipyramidal with  $c/a = 4.45$ ; space group  $C6/mmc$ ;  $a$  7.09,  $c$  18.2 Å. Hexagonal U.C. 6.

<sup>44</sup> R. L. Parker *et al.*: *Schw. Min. Pet. Mit.*, XIX, 293 (1939).

<sup>45</sup> E. I. Nefedov: *Min. Abst.*, VIII, 279 (1942).

<sup>46</sup> S. G. Gordon: *Min. Abst.*, III, 55 (1926).

<sup>47</sup> A. E. Fersman: *Am. Mineral.*, XI, 289 (1926).

<sup>48</sup> A. Lacroix: *Bull. Soc. Fr. Min.*, XXXVIII, 265 (1915); *Mineral. Madag.*, I, 300 (1922).

3. Carbonates with type formula  $\approx A_3(BX_3)_2$ 

## (a) WITHOUT ADDITIONAL ANIONS

**Fairchildite** <sup>49</sup>  $[K_2Ca(CO_3)_2]$  is hexagonal in basal plates with distinct basal cleavage.  $G. = 2.465$ .  $F. = 813^\circ C.$  in  $CO_2$  gas. Uniaxial negative with  $N_O = 1.530$ ,  $N_E = 1.48$  ca.,  $N_O - N_E = 0.05 \pm$ . Colorless. Found in wood-ash stones.

**Buetschliite** <sup>49</sup>  $[K_6Ca_2(CO_3)_5 \cdot 6H_2O]$  is probably hexagonal; it is uniaxial negative with  $N_O = 1.595$ ,  $N_E = 1.455$ ,  $N_O - N_E = 0.140$ . Found in wood-ash stones.

**Shortite** <sup>50</sup>  $[Na_2Ca_2(CO_3)_3]$  is orthorhombic pyramidal with  $a:b:c = 0.455:1:0.648$ . Space group <sup>51</sup>  $Amm$ ;  $a$  4.98,  $b$  10.97,  $c$  7.10 Å. U.C. 2. Crystals have  $\{011\}$ ,  $\{100\}$ , and  $\{00\bar{1}\}$ , etc. Distinct 010 cleavage.  $H. = 3$ .  $G. = 2.60$ . Inverts at  $200^\circ C.$  with decrepitation.  $X = c$ ,  $Y = a$ .  $(- )2V = 75^\circ$ ,  $r < v$  moderate.  $N_X = 1.531$ ,  $N_Y = 1.555$ ,  $N_Z = 1.570$ ,  $N_Z - N_X = 0.039$ . Colorless. Found in drill cores from clay shale in Wyoming.

**Pirssonite**  $[Na_2Ca(CO_3)_2 \cdot 2H_2O]$  is orthorhombic pyramidal with <sup>51a</sup>  $a:b:c = 0.564:1:0.299$ . Space group  $Fdd2$ ;  $a$  11.32,  $b$  20.06,  $c$  6.00 Å. Crystals prismatic with no cleavage.  $H. = 3-3.5$ .  $G. = 2.35$ .  $F. = 2$ . Soluble in cold acids with effervescence. The optic plane is 001;  $X = a$ .  $(+)2V = 33^\circ$ ,  $r < v$  weak.  $N_X = 1.504$  Na,  $N_Y = 1.509$ ,  $N_Z = 1.575$ ,  $N_Z - N_X = 0.071$ . Colorless. Found with gaylussite at Borax Lake, California.

**Gaylussite**  $[Na_2Ca(CO_3)_2 \cdot 5H_2O]$  is monoclinic prismatic with  $a:b:c = 1.490:1:1.444$ ,  $\beta = 101^\circ 33'$ . Crystals elongated parallel to  $a$  or wedge-shaped. Perfect 110 and poor 001 cleavages.  $H. = 2-3$ .  $G. = 1.99$ .  $F. = 1.5$ . Soluble in acid with effervescence. The optic plane and  $X$  are normal to 010;  $Z \wedge c = +14^\circ 48'$  li,  $+13^\circ 8'$  blue.  $(- )2V = 34^\circ$ ,  $r < v$  strong.  $N_X = 1.443$ ,  $N_Y = 1.516$ ,  $N_Z = 1.523$ ,  $N_Z - N_X = 0.080$  Na. Colorless. Found in lake deposits, as in Venezuela and Nevada.

## (b) WITH ADDITIONAL ANIONS

**Hydrocerussite**  $[Pb_3(OH)_2(CO_3)_2]$  is rhombohedral <sup>52</sup> with  $c/a = 0.61$  (probably hexagonal scalenohedral). Crystals tabular or lenticular with perfect basal cleavage.  $H. = 3$ .  $G. = 6.80$ .  $F. = 1.5$ . Soluble in acid with effervescence. Uniaxial negative with <sup>53</sup>  $N_O = 2.09$ ,  $N_E = 1.94$ ,  $N_O - N_E = 0.15$ . Colorless. An alteration product of lead ores.

**Hydromagnesite** <sup>54</sup>  $[Mg_5(OH)_2(CO_3)_4 \cdot 4H_2O]$  is orthorhombic dipyramidal <sup>55</sup> with  $a:b:c = 0.963:1:0.903$ . Space group  $Pmmm$ ;  $a$  8.98,  $b$  9.32,  $c$  8.42 Å. U.C. 2.

<sup>49</sup> C. Milton and J. M. Axelrod: *Bull. Geol. Soc. Am.*, LVII, 1218 (1946); *Am. Mineral.*, XXXII, 607 (1947).

<sup>50</sup> J. J. Fahey: *Am. Mineral.*, XXIV, 514 (1939).

<sup>51</sup> W. E. Richmond: *Am. Mineral.*, XXVI, 629 (1941).

<sup>51a</sup> H. T. Evans: *Am. Mineral.*, XXXIII, 261 (1948).

<sup>52</sup> L. J. Spencer and E. D. Mountain: *Mineral. Mag.*, XX, 67 (1923).

<sup>53</sup> H. E. Merwin: *Proc. Am. Soc. Test. Mat.*, XVII, 21 (1917).

<sup>54</sup> M. Fenoglio: *Min. Abst.*, VI, 474 (1937).  $a$  and  $b$  interchanged to make  $b > a$ .

<sup>55</sup> Hydromagnesite was described by A. F. Rogers (*Am. Jour. Sci.*, VI, 37, 1927) and E. S. Larsen (*U. S. Geol. Surv. Bull.* 848 (1934)) as monoclinic with  $a:b:c = 1.137:1:0.903$ ,  $\beta = 114^\circ 8'$ ,  $Y \wedge c = 42^\circ 51'$ ,  $Z = b$ ,  $(+)2V =$  moderate,  $N_X = 1.523$ ,  $N_Y = 1.527$ ,  $N_Z = 1.545$ ,  $N_Z - N_X = 0.022$ , or  $N_X = 1.527$ ,  $N_Y = 1.530$ ,  $N_Z = 1.540$ ,  $N_Z - N_X = 0.013$ . Is this a different mineral?

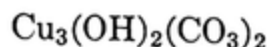
Crystals {100} tablets elongated along  $c$ . Perfect 010 cleavage and distinct 100 cleavage or parting. Constant twinning on 100, often lamellar.  $H. = 3.5$ .  $G. = 2.236$ .  $F. = 7$ . Soluble in acid with effervescence.  $X = b$ ,  $Y = c$ .  $(-)2V =$  very large.  $N_X = 1.515$ ,  $N_Y = 1.530$ ,  $N_Z = 1.544$ ,  $N_Z - N_X = 0.03$  ca. Colorless. Found chiefly in serpentine as an alteration product; also with brucite.

**Sharpite** ( $6\text{UO}_3 \cdot 5\text{CO}_2 \cdot 8\text{H}_2\text{O}$ ) is probably orthorhombic<sup>56</sup> in fibrous crusts with parallel extinction and positive elongation.  $(+)2V = ?$ ,  $N_X = 1.633$ ,  $N_Y = ?$ ,  $N_Z$  near 1.72,  $N_Z - N_X$  near 0.09. Yellowish green in color. An alteration product found in the Belgian Congo (Shinkolobwe).

**Alumohydrocalcite** [ $\text{CaAl}_2(\text{OH})_4(\text{CO}_3)_2 \cdot 3\text{H}_2\text{O}$ ] is monoclinic<sup>57</sup> with perfect 100 and distinct 010 cleavages.  $H. = 2.5$ .  $G. = 2.23$ . Soluble in acids; decomposed by hot water and by alkalis. Extinction at  $10^\circ$  to fibers ( $c$ ).  $(-)2V = 50^\circ\text{--}55^\circ$ ,  $N_X = 1.485$ ,  $N_Y = 1.553$ ,  $N_Z = 1.570$ ,  $N_Z - N_X = 0.085$ . Colorless, or rarely violet, gray, or yellow. Found in Siberia.

## AZURITE

### MONOCLINIC PRISMATIC



$$a:b:c = 0.851:1:1.76 \quad \beta = 92^\circ 25'$$

STRUC. Space group<sup>58</sup>  $P2_1/c$ ;  $a$  4.96,  $b$  5.83,  $c$  10.27 Å. U.C. 2.

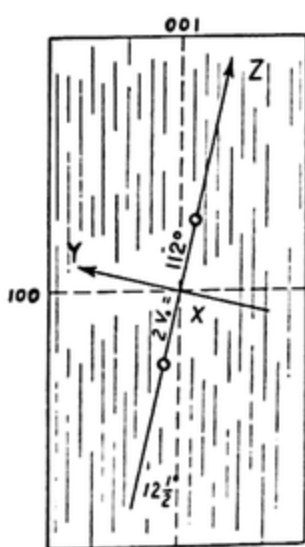


FIG. 81. The optic orientation of azurite.

PHYS. CHAR. Crystals varied and complex; thus, tabular parallel to 001 or 102, prismatic, elongated along  $b$ , or pseudorhombohedral. Twinning not common. Perfect 011 and distinct 100 cleavages.  $H. = 3.5\text{--}4$ .  $G. = 3.80$ .  $F. = 3$ . Soluble in acid with effervescence.

OPT. PROP. The optic plane and  $X$  are normal to 010;  $Z \wedge c = +12.5^\circ$ . See Fig. 81.  $(+)2V = 68^\circ$ ,  $r > v$  notable, with distinct horizontal dispersion.  $N_X = 1.730$ ,  $N_Y = 1.758$ ,  $N_Z = 1.838$ ,  $N_Z - N_X = 0.108$ . Color azure to purplish blue, and  $X < Y < Z$ . Absorption and pleochroism distinct only in thick sections.

ALTER. Azurite changes rather easily to malachite; rarely to cuprite and native copper.

OCCUR. Azurite is rather common in the oxide zone of copper deposits, especially in limestone regions, as in Arizona.

DIAG. The color and associated minerals are characteristic.

<sup>56</sup> J. Mélon: *Min. Abst.*, VII, 225 (1939).

<sup>57</sup> G. A. Bilibin: *N. Jahrb. Min.*, 1928, I, 101. *Min. Abst.*, III, 472 (1930).

<sup>58</sup> H. Brasseur: *Zeit. Krist.*, LXXXII, 195 (1932).



4. Carbonates with type formula  $\approx A_2BX_3$ 

## (a) WITHOUT ADDITIONAL ANIONS

**Teschemacherite** ( $\text{H}\text{N}\text{H}_4\text{CO}_3$ ) is orthorhombic dipyramidal with  $a:b:c = 0.676:1:0.812$ . Space group <sup>59</sup>  $Pccn$ ;  $a$  7.29,  $b$  10.79,  $c$  8.76 Å. U.C. 8. Perfect 110 cleavage.  $H. = 1.5$ .  $G. = 1.57$ .  $X = a$ ;  $Y = b$ .  $(- )2V = 41^\circ 38'$ ,  $r < v$  weak.  $N_X = 1.4227$ ,  $N_Y = 1.5358$ ,  $N_Z = 1.5545$ ,  $N_Z - N_X = 0.1318$  (artificial). Colorless. Found in guano deposits.

**Kalicinite** ( $\text{HKCO}_3$ ) is monoclinic prismatic with  $a:b:c = 2.638:1:0.647$ ,  $\beta = 103^\circ 25'$ . Space group <sup>60</sup>  $P2_1/a$ ;  $a$  15.01,  $b$  5.69,  $c$  3.68 Å. U.C. 4. Crystals domatic or tabular with 100, 001, and 101 cleavages.  $G. = 2.16$ .  $X \wedge c = -30^\circ$ ,  $Y = b$ .  $(- )2V = 81^\circ 30'$ ,  $N_X = 1.380$ ,  $N_Y = 1.482$ ,  $N_Z = 1.573$ ,  $N_Z - N_X = 0.193$  (artificial <sup>61</sup>). Colorless.

## NAHCOLITE

## MONOCLINIC PRISMATIC

 $\text{HNaCO}_3$ 

$$a:b:c = 0.765:1:0.358 \quad \beta = 93^\circ 19'$$

STRUC. Space group <sup>62</sup>  $P2_1/n$ ;  $a$  7.51,  $b$  9.70,  $c$  3.53 Å. U.C. 4.

PHYS. CHAR. Crystals {010} tablets bounded by {110}, {111}, and  $\{11\bar{1}\}$ , often

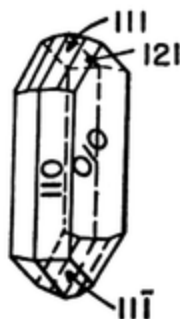


FIG. 82. A crystal habit of nahcolite.

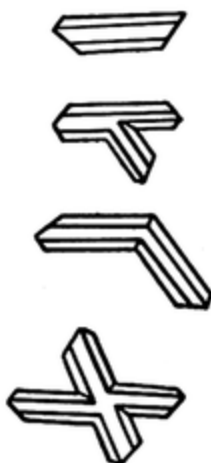


FIG. 83. Nahcolite crystals.

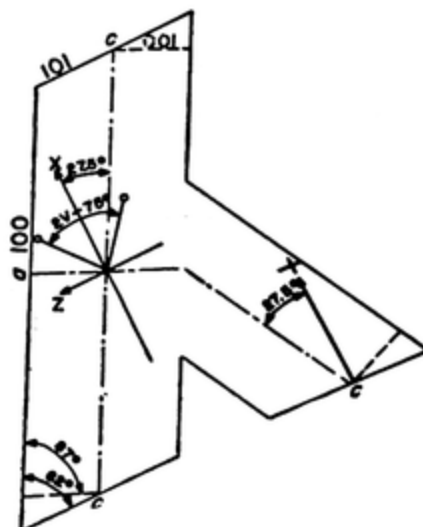


FIG. 84. The optic orientation of nahcolite twins.

twinned on 101, with composition face  $\perp$  101. See Figs. 82 and 83. Perfect 101 and distinct 111 cleavages.  $G. = 2.22$ . Soluble in  $\text{H}_2\text{O}$ .

OPT. PROP. The optic plane is 010;  $X \wedge c = -27.5^\circ$  ( $X$  normal <sup>63</sup> to 101). See Fig. 84.  $(- )2V = 75^\circ$ ,  $r < v$ .  $N_X = 1.375$ ,  $N_Y = 1.505$ ,  $N_Z = 1.583$ ,  $N_Z - N_X$

<sup>59</sup> R. C. L. Mooney: *Phys. Rev.*, XXXIX, 861 (1932).

<sup>60</sup> J. Dhar: *Curr. Sci.*, IV, 867 (1936).

<sup>61</sup> H. E. Merwin: *Int. Crit. Tab.*, VII, 27 (1930).

<sup>62</sup> W. H. Zachariasen: *Jour. Chem. Phys.*, I, 634 (1933).

<sup>63</sup> H. L. Robson: personal communication, Dec. 3, 1930

= 0.208.<sup>64</sup> The extinction angle is about half the angle between the *c* axes in 101 twins, and so the substance is characterized<sup>63</sup> by the simultaneous extinction of the two parts of the twin. Colorless or white.

**OCCUR.** Found in salt lake deposits with trona and thermonatrite, as at Searles Lake, California.

**Natron** ( $\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$ ) is monoclinic prismatic with  $a:b:c = 1.419:1:1.483$ ,  $\beta = 122^\circ 20'$ . Distinct 001 cleavage.  $G. = 1.46$ . Dehydrates very easily.  $X = b$ ;  $Z \wedge c = -41^\circ$ .  $(- )2V = 71^\circ$ ,  $r > v$  weak with weak crossed dispersion.  $N_X = 1.405$ ,  $N_Y = 1.425$ ,  $N_Z = 1.440$ ,  $N_Z - N_X = 0.035$  (artificial). Colorless.

**Trona** ( $\text{HNa}_3(\text{CO}_3)_2 \cdot 2\text{H}_2\text{O}$ ) is monoclinic prismatic with  $a:b:c = 2.843:1:2.949$ ,  $\beta = 103^\circ 29'$ . Crystals {001} tablets or elongated parallel to *b*. Perfect 100 cleavage.  $H. = 2.5-3$ .  $G. = 2.14$ .  $F. = 1.5$ . Soluble in water.  $X = b$ ;  $Y \wedge c = -17^\circ$ .  $(- )2V = 72^\circ$ ,  $r < v$  marked.  $N_X = 1.412$ ,  $N_Y = 1.492$ ,  $N_Z = 1.540$ ,  $N_Z - N_X = 0.128$ .<sup>65</sup> Colorless. Common in some arid regions as an efflorescence, or salt-lake deposit.

### (b) WITH ADDITIONAL ANIONS

**Northupite** [ $\text{Na}_3\text{MgCl}(\text{CO}_3)_2$ ] is isometric diploidal. Space group<sup>66</sup>  $Fd\bar{3}$ ;  $a$  14.13 Å. U.C. 16. No cleavage.  $H. = 4$ .  $G. = 2.38$ .  $F. = 1$  with frothing. Soluble in acid with effervescence. Isotropic with  $N = 1.5144$  Na. May show abnormal birefringence<sup>67</sup> with twinning. Colorless. Found in clay at a depth of 450 feet at Borax Lake, California.

**Phosgenite**<sup>68</sup> ( $\text{Pb}_2\text{Cl}_2\text{CO}_3$ ) is ditetragonal dipyramidal with  $c/a = 1.091$ . Space group  $P4/mbm(?)$ ;  $a$  8.13,  $c$  8.86 Å. U.C. 4. Crystals prismatic or basal plates or acute pyramidal. Distinct 110, 100 and poor 001 cleavages. Piezoelectric.  $H. = 3$ .  $G. = 6.0$ .  $F. = 1$ . Soluble in dilute  $\text{HNO}_3$  with effervescence. Uniaxial positive with<sup>69</sup>  $N_O = 2.118$ ,  $N_E = 2.145$ ,  $N_E - N_O = 0.027$ . Color white, gray, or yellow. Colorless in section. Found in lead deposits, as at Laurium, Greece.

**Dawsonite** ( $\text{NaAl}(\text{OH})_2\text{CO}_3$ ) is orthorhombic with  $a:b:c = 0.648:1:0.534$ . Crystals acicular parallel to *c*, or bladed. Perfect 110 cleavage.  $H. = 3$ .  $G. = 2.4$ .  $F. = 4.5-5$ . Soluble in  $\text{HCl}$  with effervescence.  $X = a$ ,  $Y = c$ .  $(- )2V = 77^\circ$ ,  $r < v$  weak.  $N_X = 1.466$ ,  $N_Y = 1.542$ ,  $N_Z = 1.596$ ,  $N_Z - N_X = 0.130$ . Color white. Found as an alteration product.

## MALACHITE

## MONOCLINIC PRISMATIC



$$a:b:c = 0.791:1:0.269 \quad \beta = 98^\circ 44'$$

**COMP.** Additional water (adsorbed?) may be present.<sup>70</sup> Copper may be replaced, in part, by zinc; with  $\text{Cu}:\text{Zn} = 9:2$  the mineral is sometimes

<sup>64</sup> W. F. Foshag: *Am. Mineral.*, XXV, 769 (1940).

<sup>65</sup> E. S. Larsen: *U. S. Geol. Surv. Bull.* 679 (1921) and 848 (1934).

<sup>66</sup> B. Gossner and I. Koch: *Zeit. Krist.*, LXXX, 455 (1931).

<sup>67</sup> V. von Zepharovich: *Zeit. anorg. Chem.*, LXXXVII, H 15 (1893).

<sup>68</sup> I. Oftedal: *Norsk Geol. Tidssk.*, XXIV, 79 (1945); *Min. Abst.*, IX, 229 (1946). See also L. G. Sillen and R. Pettersson: *Ark. Kemi, Min. Geol.*, XXIA, No. 13 (1946).

<sup>69</sup> H. Baumhauer: *Zeit. Kryst.*, XLVII, 9 (1909).

<sup>70</sup> O. Binder: *Comp. Rend. Acad. Sci. Paris*, CCIV, 1200 (1937).

called *cuprozinkite*; <sup>71</sup> with Cu:Zn = 3:2, it has been called *rosasite*.<sup>72, 73, 73a</sup>

STRUC. Space group <sup>74</sup>  $P2_1/a$ ;  $a$  9.49,  $b$  12.00,  $c$  3.24 Å. U.C. 4. For *rosasite*: <sup>72</sup>  $a$  9.40,  $b$  12.30,  $c$  2.43 Å.

PHYS. CHAR. Crystals acicular to fibrous in tufts, etc. Twinning common on 100. Perfect  $\bar{2}01$  and distinct 010 cleavages.  $H. = 6$ .  $G. = 4.05$ .  $F. = 2$ . Soluble in  $HNO_3$  with effervescence.

OPT. PROP. The optic plane is 010;  $X \wedge c = +23.5^\circ$ , or  $X \wedge \bar{2}01$  cleavage =  $85^\circ$ . See Fig. 85.  $X \wedge c = 21^\circ$  to  $23^\circ$  in *cuprozinkite*.  $(- )2V = 43^\circ$ ,  $r < v$  distinct in air, though  $r > v$  marked in the crystal. Weak inclined dispersion.  $N_X = 1.655$ ,  $N_Y = 1.875$ ,  $N_Z = 1.909$ ,  $N_Z - N_X = 0.254$ .<sup>65</sup>  $N_X = 1.703$ . For *rosasite* <sup>73a</sup>  $(- )2V =$  small,  $N_X = 1.672$ ,  $N_Y = 1.83$ ,  $N_Z = 1.83$ ,  $N_Z - N_X = 0.158$ ; in rectangular plates of crushed *rosasite*,<sup>73</sup> extinction is parallel, elongation is negative,  $N_1 = 1.71$ ,  $N_2 > 1.745$ . Color green with  $X =$  nearly colorless,  $Y =$  yellowish green,  $Z =$  deep green. Pleochroism rather weak.

OCCUR. Malachite is common in the oxide zone of copper deposits, especially those in limestone areas.

DIAG. Malachite differs from *atacamite* in having inclined extinction of the fibers, and extreme birefringence; also, in malachite the best cleavage is across the elongation and a little oblique to the acute bisectrix, while a second cleavage usually shows twinning on 100 with an extinction angle of  $23^\circ$  and an optic normal interference figure; *atacamite* and *brochantite* have only one distinct cleavage (010) which is parallel to their elongation and normal to the acute bisectrix.

**Artinite** ( $Mg_2(OH)_2CO_3 \cdot 3H_2O$ ) is monoclinic <sup>75</sup> with  $a:b:c = 5.305:1:1.975$ ,  $\beta = 99^\circ 45'$  (Heritsch),<sup>76</sup>  $98^\circ 56'$  (Hurlbut).<sup>76</sup> Space group  $Pm$  or  $P2$ ;  $a$  16.66,  $b$  3.14,  $c$  6.20 Å. U.C. 1.  $H. = 2$ .  $G. = 2.03$ . Good 100 and distinct 001 cleavages. An optic axis is normal to the better cleavage (100). Fibers elongated along  $b$ ;  $Y = b$ ,  $Z \wedge c = +30^\circ$ ,  $(- )2V = 60^\circ$ ,  $N_X = 1.488$ ,  $N_Y = 1.534$ ,  $N_Z = 1.556$ ,  $N_Z - N_X = 0.068$ . Colorless. Found in serpentine, as in Styria and Serbia; also in veins in *brucite* at Luning, Nevada.

<sup>71</sup> F. K. Biehl: *Min. Abst.*, I, 202 (1921).

<sup>72</sup> C. Lauro: *Per. Min. Roma*, VIII, 151 (1937); *Min. Abst.*, VII, 216 (1938).

<sup>73</sup> C. Perrier: *Min. Abst.*, II, 240 (1924).

<sup>73a</sup> T. Barth and H. Berman: *Chem. Erde*, V, 22 (1930).

<sup>74</sup> L. S. Ramsdell and C. W. Wolfe: *Am. Mineral.*, XXXV, 119 (1950).

<sup>75</sup> H. Heritsch: *Cent. Mineral.*, 1940A, 25; M. Fenoglio: *Per. Min. Roma*, XIII, 1 (1942).

<sup>76</sup> C. S. Hurlbut: *Am. Mineral.*, XXXI, 365 (1946).

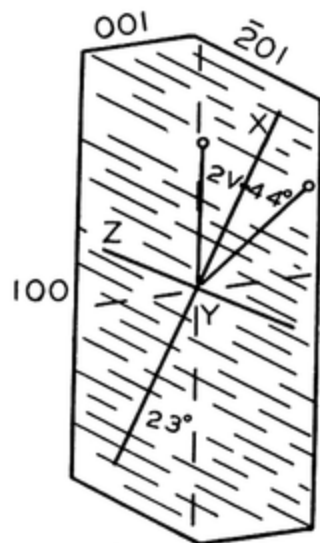


FIG. 85. The optic orientation of malachite.

**Beyerite** <sup>77</sup>  $[\text{CaBi}_2\text{O}_2(\text{CO}_3)_2]$  is ditetragonal dipyramidal with  $c/a = 5.759$ ,  $a = 3.78$ ,  $c = 21.77 \text{ \AA}$ . Crystals are basal plates.  $H. = 3$ , or less.  $G. = 6.56$ . Uniaxial negative with  $N_O = 2.13$ ,  $N_E = 1.99$ ,  $N_O - N_E = 0.14$ . May have a small optic angle. Again  $N_O = 2.11$ ,  $N_E = 1.94$ ,  $N_O - N_E = 0.17$ . Color yellow to white. Found in Saxony and California.

**Bismutite** <sup>77</sup>  $(\text{Bi}_2\text{O}_2\text{CO}_3)$  is unknown in distinct crystals, being usually fibrous or earthy. Often contains (adsorbed) water.  $H. = 3.5$ .  $G. = 6.6-7.6$ .  $F. = 1$ . Soluble in  $\text{HNO}_3$  with effervescence. Fibers have parallel extinction and positive elongation. An optic axis normal to a good cleavage. Biaxial <sup>66</sup> with  $N = 2.12$  to  $2.30$  and  $N_Z - N_X = \text{about } 0.05$ . Color yellow, brown, green, white, gray, blue. Found in some ore deposits.

**Waltherite** <sup>77</sup> is a bismuth carbonate, which is probably monoclinic; prism angle is  $116^\circ$ .  $c/a = 5.42 \text{ \AA}$ . Prismatic and pinacoidal cleavages.  $H. = 4$ .  $G. = 5.3$  or more. Color brown to green. The brown crystals <sup>66</sup> have  $Y = b$  and  $X \wedge c = 16^\circ$ ;  $(-)2V = 75^\circ$ ,  $r < v$ ;  $N_Y = 1.91 ca.$   $N_Z - N_X = \text{strong}$ . Weakly pleochroic with  $X = Y < Z$ . The green crystals <sup>78</sup> have  $2V_X = 90^\circ$  or more and then  $r > v$ ; they have the same X-ray pattern, but higher refringence and stronger birefringence than the brown crystals. Found in Bohemia.

## 5. Carbonates with type formula $\approx \text{A}_3\text{BX}_3$

**Aurichalcite**  $[(\text{Zn}, \text{Cu})_6(\text{OH})_6(\text{CO}_3)_2]$  is monoclinic with <sup>78</sup>  $a:b:c = 2.133:1:0.849$ ,  $\beta = 95^\circ 45'$ . Space group  $C2/m$ ,  $C2$ , or  $Cm$ ;  $a = 13.45$ ,  $b = 6.31$ ,  $c = 5.36$ . U.C. 2. (Measured on hydrozinkite.) With no copper it is called *hydrozinkite*. Crystals thin blades parallel to 100 (or 001) elongated parallel to  $c$  (or  $a$ ); also fibers parallel to  $c(?)$ . Perfect 100 (or 001?) cleavage.  $H. = 2-2.5$ .  $G. = 3.6-3.64+$ .  $G. = 4.0$  for hydrozinkite.  $F. = 7$ . Soluble in  $\text{HCl}$  with effervescence.  $X = b$ ;  $Z \wedge a = 13^\circ$  (Larsen <sup>68</sup>);  $40^\circ$  (Prider <sup>79</sup>);  $41^\circ-42^\circ$  (Shannon <sup>80</sup>).  $(-)2V = \text{very small to } 40^\circ$ ,  $r < v$  distinct to strong.  $N_X = 1.63-1.655$ ,  $N_Y = ?$ ,  $N_Z = 1.73-1.75$ ,  $N_Z - N_X = 0.08-0.11$ . Relations between variations in composition and properties are not yet clear, perhaps because the  $\text{H}_2\text{O}:\text{CO}_2$  ratio varies as well as the  $\text{CuO}:\text{ZnO}$  ratio. Color pale green or blue with  $X = \text{nearly colorless}$ ,  $Y$  and  $Z$  pale greenish (or bluish). Hydrozinkite is colorless. Found in the oxide zone of copper-zinc ore deposits, occasionally as an alteration product of malachite.

**Loseyite**  $[(\text{Mn}, \text{Zn})_7(\text{OH})_{10}(\text{CO}_3)_2]$  is monoclinic with  $a:b:c = 0.70:1:0.62$ ,  $\beta = 94^\circ 30'$ . Crystals elongated parallel to  $b$  with no visible cleavage.  $H. = 3$ .  $G. = 3.27$ . Soluble in  $\text{HCl}$ .  $Y = b$ .  $(+)2V = 64^\circ$ ,  $r > v$ .  $N_X = 1.637$ ,  $N_Y = 1.648$ ,  $N_Z = 1.676$ ,  $N_Z - N_X = 0.039$ . Color bluish white; colorless in thin section. Known only at Franklin, New Jersey.

**Zaratite**  $[\text{Ni}_3(\text{OH})_4\text{CO}_3 \cdot 4\text{H}_2\text{O}]?$  is amorphous, often banded in crusts, etc.  $H. = 3$ .  $G. = 2.6 \pm$ .  $F. = 7$ . Soluble in  $\text{HCl}$  with effervescence. Isotropic with  $N = 1.56$  to  $1.61$ . Also weakly birefringent <sup>81</sup> with parallel extinction and positive

<sup>77</sup> C. Frondel: *Am. Mineral.*, XXVIII, 521 (1943). E. W. Heinrich: *Am. Mineral.*, XXXII, 660 (1947).

<sup>78</sup> G. D'Achiardi in Doelter: *Hdb. Mineralchem.*, I, 474; F. K. Biehl: *Min. Abst.*, I, 203 (1921). L. S. Ramsdell: *Am. Mineral.*, XXXII, 207 (1947), says that aurichalcite and hydrozinkite are not isomorphous.

<sup>79</sup> R. T. Prider: *Mineral. Mag.*, XXVI, 60 (1941).

<sup>80</sup> E. V. Shannon: *U. S. Nat. Mus. Bull.* 131, 266 (1926).

<sup>81</sup> F. Slavik: *Am. Mineral.*, XI, 279 (1926).

elongation and  $N = 1.565 \pm$ ; also  $N = 1.589$ . Emerald green color. Found with chromite in serpentine, as at Texas, Pennsylvania.

## 6. Nitrates

**Nitratite** ( $\text{NaNO}_3$ ) or *soda niter* is hexagonal scalenohedral with  $c/a = 0.828$ , homeomorphous with calcite. Space group  $^{82} R\bar{3}c$ ;  $a$  6.32 Å,  $\alpha = 47^\circ 14'$ . Perfect 10 $\bar{1}$ 1 cleavage.  $H. = 1.5$ – $2$ .  $G. = 2.27$ .  $F. = 1$ ; deflagrates on heating. Deliquescent. Soluble in water. Uniaxial negative with extreme birefringence.  $N_O = 1.585$ ,  $N_E = 1.337$ ,  $N_O - N_E = 0.248$ .  $N_E'$  on the cleavage is 1.467. Color white. Found with gypsum, halite, etc., as a surface formation in desert regions, as in Humboldt County, Nevada.

**Niter** ( $\text{KNO}_3$ ) or *saltpeter* is orthorhombic dipyramidal  $^{83}$  with  $a:b:c = 0.591:1:0.701$ , homeomorphous with aragonite.  $a$  5.40,  $b$  9.14,  $c$  6.41 Å. U.C. 4. Crystals equant or vertical acicular with perfect 011 and poor 010 and 100 cleavages.  $H. = 2$ .  $G. = 2.1$ .  $F. = 1$ . Deflagrates vividly on coal giving violet flame color. Soluble in water. The optic plane is 100;  $X = c$ .  $(- )2V = 7^\circ$ ,  $r < v$  strong.  $N_X = 1.335$ ,  $N_Y = 1.505$ ,  $N_Z = 1.506$ ,  $N_Z - N_X = 0.171$ . Colorless. Inverts to a rhombohedral phase at  $339^\circ \text{C}$ . (space group  $^{84} R\bar{3}m$ ;  $a$  4.365 Å). Niter is found in caves and on the surface in desert regions, as in Persia, Egypt, etc.

**Gerhardtite**  $[\text{Cu}_4(\text{OH})_6(\text{NO}_3)_2]$  is orthorhombic dipyramidal with  $a:b:c = 0.922:1:1.156$ . Crystals thick basal tablets with striated pyramid zones. Perfect 001 and distinct 100 cleavages.  $H. = 2$ .  $G. = 3.43$ .  $F. = 2$ . Soluble in dilute acid. The optic plane  $^{85}$  is 010;  $Z = c$ .  $(+ )2V = \text{large}$ ,  $r < v$  very strong.  $N_X = 1.703$ ,  $N_Y = 1.713$ ,  $N_Z = 1.722$ ,  $N_Z - N_X = 0.019$ . Color emerald green with  $X$  and  $Y = \text{green}$ ,  $Z = \text{blue}$ . Found in copper ores, as at Jerome, Arizona.

**Nitromagnesite**  $[\text{Mg}(\text{NO}_3)_2 \cdot n\text{H}_2\text{O}]$  is monoclinic(?); fibrous.  $F. = \text{easy}$ . Soluble in water. Has a bitter taste.  $(- )2V = 5^\circ$ ,  $r < v$  weak.  $N_X = 1.344$ ,  $N_Y = 1.506$ ,  $N_Z = 1.506$ ,  $N_Z - N_X = 0.162$ . Colorless. Found in caves with nitrocalcite, and on magnesian rocks. Artificial  $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$  is monoclinic with  $a:b:c = 0.519:1:0.970$ ,  $\beta = 101^\circ 56'$ ; crystals long prismatic with perfect 110 cleavages at  $54^\circ 48'$ .

## 7. Iodates

**Salesite**  $[\text{Cu}(\text{OH})\text{IO}_3]$  is orthorhombic dipyramidal  $^{86}$  with  $a:b:c = 0.444:1:0.624$ . Space group  $Pcmn$ ;  $a$  4.78,  $b$  10.77,  $c$  6.70 Å. U.C. 4. Crystals prismatic with perfect 110 cleavage.  $H. = 3$ .  $G. = 4.77$ . The optic plane is 001;  $X = a$ .  $(- )2V = 0^\circ$ – $5^\circ$ ,  $r > v$  extreme (uniaxial in blue).  $N_X = 1.706$ ,  $N_Y = 2.070$ ,  $N_Z = 2.075$ ,  $N_Z - N_X = 0.289$ . Color bluish green with  $X = \text{colorless}$ ,  $Y = \text{light bluish green}$ ,  $Z = \text{bluish green}$ . Discovered in the copper ores at Chuquicamata, Chile.

**Lautarite**  $[\text{Ca}(\text{IO}_3)_2]$  is monoclinic prismatic  $^{2a}$  with  $a:b:c = 0.633:1:0.646$ ,  $\beta = 106^\circ 22'$ . Space group  $^{87} P2_1/c$ ;  $a$  7.18,  $b$  11.38,  $c$  7.32 Å. U.C. 4. Crystals

$^{82}$  R. W. G. Wyckoff: *Phys. Rev.*, XVI, 149 (1920).

$^{83}$  C. Hermann: *Zeit. Krist.*, LXVIII, 257 (1928). W. H. Zachariasen: *Skr. Norske Vidensk. 7* (1928).

$^{84}$  T. F. W. Barth: *Zeit. phys. Chem.*, XLIII, 448 (1939).

$^{85}$  J. Thoreau: *Ann. Soc. Geol. Belg.*, XLVI, B285 (1924); *Min. Abst.*, III, 52 (1926).

$^{86}$  C. Palache, O. W. Jarrell, and W. E. Richmond: *Am. Mineral.*, XXIV, 388 (1939).

$^{87}$  B. Gossner and F. Mussnug: *Zeit. Krist.*, LXXV, 410 (1930).

prismatic with distinct 011 cleavage.  $H. = 4$ .  $G. = 4.59$ .  $F. = 1.5$ . Soluble in HCl. The optic plane is 010;  $X \wedge c = 25^\circ$ .  $(+)2V = \text{nearly } 90^\circ$ ,  $r > v$ .  $N_X = 1.792$ ,  $N_Y = 1.840$ ,  $N_Z = 1.888$ ,  $N_Z - N_X = 0.096$ . Colorless to yellow. Found in caliche in Peru.

**Bellingerite**  $[3\text{Cu}(\text{IO}_3)_2 \cdot 2\text{H}_2\text{O}]$  is triclinic pinacoidal<sup>88</sup> with  $a:b:c = 0.926:1:1.015$ ,  $\alpha = 105^\circ 6'$ ,  $\beta = 96^\circ 58'$ ,  $\gamma = 92^\circ 55'$ . Space group  $P\bar{1}$ ;  $a$  7.22,  $b$  7.82,  $c$  7.92 Å. U.C. 3. Crystals {100} tablets and prisms with many faces. No cleavage.  $H. = 4$ .  $G. = 4.89$ . Color pale green. On 100,  $X' \wedge 001 = 53^\circ$ .  $(+)2V = \text{medium}$ ,  $r > v$ .  $N_X = 1.89$ ,  $N_Y = 1.90$ ,  $N_Z = 1.99$ ,  $N_Z - N_X = 0.10$ . Found in fissures in highly altered granite at Chuquicamata, Chile.

**Dietzeite**  $(\text{CaI}_2\text{O}_6 \cdot \text{CaCrO}_4)$  is monoclinic prismatic with  $a:b:c = 1.392:1:1.922$ ,  $\beta = 106^\circ 32'$ . Space group<sup>87</sup>  $P2_1/c$ ;  $a$  10.16,  $b$  7.30,  $c$  14.03 Å. U.C. 4. Crystals prismatic or {100} tablets with poor 100 cleavage.  $H. = 3-4$ .  $G. = 3.62$ .  $F. = 1.5$ . Soluble in hot water;  $\text{CaI}_2\text{O}_6 \cdot 6\text{H}_2\text{O}$  separates on cooling. According to Osann<sup>89</sup> the optic plane is normal to 010, the optic sign is +, and  $Y \wedge c = 6^\circ$ . According to Larsen<sup>65</sup> the optic plane is 010, the optic sign is -, and the 100 cleavage is sensibly normal to X.  $N_X = 1.825$ ,  $N_Y = 1.842$ ,  $N_Z = 1.857$ ,  $N_Z - N_X = 0.032$ .  $2V = 86^\circ$ ,  $r < v$  very strong with marked inclined dispersion. Color sulfur to dark golden yellow. Found in the desert of Atacama, Chile.

<sup>88</sup> H. Berman and C. W. Wolfe: *Am. Mineral.*, XXV, 505 (1940).

<sup>89</sup> A. Osann: *Zeit. Krist.*, XXIII, 588 (1894).



## VI. OTHER MINERAL CARBON COMPOUNDS

This division includes all natural compounds of carbon (except carbonates) which are considered to belong to inorganic nature. Coal and succinite are doubtless derived from organisms, but they have been under the conditions of the inorganic world so long that they are commonly regarded as minerals.

**Julienite**  $[\text{Na}_2\text{Co}(\text{CSN})_4 \cdot 8\text{H}_2\text{O}]$  is tetragonal<sup>1</sup> with  $c/a = 0.603$ ;  $a$  9.22,  $c$  5.56 Å. U.C. 1. Crystals acicular or rarely tabular.  $G. = 1.68$ . Very soluble in alcohol or water. Uniaxial positive with  $N_O = 1.556$ ,  $N_E = 1.642$ ,  $N_E - N_O = 0.086$ . Color deep blue. Found in talc in Katanga, Belgian Congo.

**Weddellite**  $(\text{CaC}_2\text{O}_4 \cdot 2\text{H}_2\text{O})$  is tetragonal dipyramidal<sup>2</sup> with  $c/a = 0.594$ . Space group  $I4/m$ ;  $a$  12.40,  $c$  7.37 Å. U.C. 8. Crystals pyramidal; encrusting.  $H. = 4$ .  $G. = 1.94$ ? Uniaxial positive with  $N_O = 1.523$ ,  $N_E = 1.544$ ,  $N_E - N_O = 0.021$ . Colorless. Found in deep-sea deposits.

**Mellite**  $(\text{Al}_2\text{C}_{12}\text{O}_{12} \cdot 18\text{H}_2\text{O})$  is tetragonal with  $c/a = 1.055$ ;  $a$  22.0,  $c$  23.3 Å. Space group<sup>3</sup>  $P4_1$  or  $P4_32$ . U.C. 16. Crystals pyramidal with poor 101 cleavage.  $H. = 2-2.5$ .  $G. = 1.65$ . Decomposed by boiling water; soluble in  $\text{HNO}_3$ . Uniaxial negative with  $N_O = 1.539$  D,  $N_E = 1.511$ ,  $N_O - N_E = 0.028$ . Color honey yellow, reddish, white. Found in brown coal. Uncommon.

**Earlandite**<sup>2</sup>  $[\text{Ca}_3(\text{C}_6\text{H}_5\text{O}_7)_2 \cdot 4\text{H}_2\text{O}]$  is biaxial.  $G. = 1.95$ .  $(+ )2V = 60^\circ$  calc.  $N_X = 1.515$ ,  $N_Y = 1.530$ ,  $N_Z = 1.580$ ,  $N_Z - N_X = 0.065$ . Found in deep-sea deposits.

**Humboldtite**<sup>4</sup>  $(\text{FeC}_2\text{O}_4 \cdot 2\text{H}_2\text{O})$  or *oxalite* is orthorhombic with  $a:b:c = 0.773:1:1.104 \pm$ . Crystals prismatic with perfect 110 and distinct 100 and 010 cleavages.  $H. = 2$ .  $G. = 2.28$ . Soluble in acid. The optic plane is 010;  $Z = c$ .  $(+ )2V =$  large.  $N_X = 1.494$ ,  $N_Y = 1.561$ ,  $N_Z = 1.692$ ,  $N_Z - N_X = 0.198$ . Color yellowish with  $X =$  pale yellowish green,  $Y =$  pale greenish yellow,  $Z =$  intense yellow. Found in brown coal and black shales.

**Oxammite**  $[(\text{NH}_4)_2\text{C}_2\text{O}_4 \cdot \text{H}_2\text{O}]$  is orthorhombic disphenoidal with  $a:b:c = 0.78:1:0.37$ . Crystals prismatic or {100} tablets with poor 001 cleavage. Soft.  $G. =$

<sup>1</sup> A. Schoep and V. Billiet: *Zeit. Krist.*, XCI, 229 (1935).

<sup>2</sup> F. A. Bannister and M. H. Hey: *Discovery Reports*, XIII, 60 (1936); *Science*, XCV, 431 (1942).

<sup>3</sup> T. F. W. Barth and C. J. Ksanda: *Am. Mineral.*, XVIII, 8 (1933).

<sup>4</sup> E. Manasse: *Rend. Accad. Lincei Roma*, XIX, 5a, 138 (1910).

1.48±. F. = easy. Soluble in water. The optic plane is 100;  $X = c$ .  $(- )2V = 62^\circ$ ,  $r < v$  distinct. The artificial salt has  $N_X = 1.438$ ,  $N_Y = 1.547$ ,  $N_Z = 1.595$ ,  $N_Z - N_X = 0.157$ . Color white. Found in guano.

**Whewellite** ( $\text{CaC}_2\text{O}_4 \cdot \text{H}_2\text{O}$ ) is monoclinic with  $a:b:c = 0.87:1:1.37$ ,  $\beta = 107^\circ 18'$ . Crystals complex; twinning on  $10\bar{1}$ ; 001, 010, 110, and 101 cleavages. H. = 2.5. G. = 2.23. F. = 7. Soluble in acid. The optic plane<sup>5</sup> and X are normal to 010;  $Z \wedge c = -29^\circ$  ( $29^\circ$  to  $31^\circ$  for different wave lengths).<sup>6</sup>  $(+ )2E = 84^\circ$ ;  $2V = 51^\circ$ ,  $r < v$  weak.  $N_X = 1.490$ ,  $N_Y = 1.555$ ,  $N_Z = 1.650$ ,  $N_Z - N_X = 0.160$ . Again:<sup>7</sup>  $(+ )2V = 80-85^\circ$ ,  $N_X = 1.495$ ,  $N_Y = 1.565$ ,  $N_Z = 1.665$ ,  $N_Z - N_X = 0.170$ .  $Z \wedge c = 24^\circ$ . Colorless. Found in calcite veins in coal and shale; also in plant tissues.

**Kladnoite** [ $\text{C}_6\text{H}_4(\text{CO})_2\text{NH}$ ] is monoclinic<sup>8</sup> in {100} laths with {110}, {230}, etc. G. = 1.47. F. = 233-235° C. The optic plane and Z are normal to 010;  $X \wedge c = 74^\circ$  ca.,  $(+ )2V = 25^\circ$  calc.  $N_X = 1.501$ ,  $N_Y = 1.519$ ,  $N_Z = 1.755$ ,  $N_Z - N_X = 0.254$ . Found in burning coal heaps at Kladno, Bohemia.

**Paraffin** ( $\text{C}_n\text{H}_{2n+2}$ , with  $n > 15$ ) includes many substances, some being "liquid crystals" at certain temperatures. When  $n$  is even the crystals are orthorhombic; with  $n$  odd, the crystals are said to be monoclinic (in some cases, at least); upon heating, inversion to a hexagonal phase occurs near the melting point in the series from  $\text{C}_{21}$  to  $\text{C}_{29}$ . Certain orthorhombic crystals have<sup>9</sup>  $a:b:c = 0.666:1:0.342$ . Others are very similar. Space group  $Pnam(?)$ .  $a$  4.93,  $b$  7.40,  $c$  2.534 Å. U.C. 4. Crystals thin basal plates. H. = 1. G. = 0.9. F. increases from  $23^\circ$  for  $\text{C}_{17}\text{H}_{36}$  to  $74^\circ$  for  $\text{C}_{35}\text{H}_{72}$ . Burns readily. Soluble in ether; insoluble in acid. Reported<sup>10</sup> as uniaxial positive with  $N_O = 1.478$  to 1.503,  $N_E = 1.525$  to 1.545,  $N_E - N_O = 0.047$  to 0.042; also<sup>11</sup>  $N_O = 1.502$ ,  $N_E = 1.550$ ,  $N_E - N_O = 0.048$ . But<sup>12</sup>  $2E$  (while small or  $0^\circ$  in mix-crystals) varies from  $0^\circ$  to  $41^\circ$ ; the optic plane and X are normal to 100 and  $Z = c$ . Optically +,  $N_Y$  and  $N_X$  (very nearly equal) vary between 1.50 and 1.52 for paraffins between  $\text{C}_{21}\text{H}_{44}$  and  $\text{C}_{32}\text{H}_{66}$ . Crystals normal to Z produce notable dextrorotation<sup>12</sup> of one ray, causing maximum light to be seen not at  $45^\circ$  from extinction. Colorless. When grown on a slide or crushed under a cover glass all crystals or fragments are oriented normal to the acute bisectrix (Z). Found in cavities in basalt.

**Ozocerite** is a kind of paraffin. (Nearly) uniaxial positive with  $N_O = 1.515$ ,  $N_E = 1.54$ ,  $N_E - N_O = 0.025$ . Also biaxial<sup>13</sup> of small optic angle. Found in seams in coal or bituminous shale in Utah.

**Hatchettite** is a kind of paraffin. H. = 1. G. = 0.96. F. =  $80^\circ$  C. ( $\therefore$  formula about  $\text{C}_{40}\text{H}_{82}$ ). Soluble in oils but not in acids. Burns readily. Nearly uniaxial and positive.<sup>14</sup>  $N_O = 1.480$ ,  $N_E = 1.502$ ,  $N_E - N_O = 0.022$ . Biaxial and probably

<sup>5</sup> E. T. Wherry: *Jour. Wash. Acad. Sci.*, XII, 196 (1922).

<sup>6</sup> J. V. Kaspar: *Min. Abst.*, V, 189 (1933).

<sup>7</sup> V. A. Kalyuzhnyia: *Min. Abst.*, X, 502 (1949).

<sup>8</sup> R. Rost: *Min. Abst.*, IX, 186 (1946).

<sup>9</sup> C. W. Bunn: *Trans. Faraday Soc.*, XXXV, 482 (1939).  $a$  and  $b$  interchanged to make  $b > a$ .

<sup>10</sup> W. Camerer: *Ann. Phys.*, LIV, 84 (1895), for paraffin with F. =  $40^\circ$  to  $80^\circ$ .

<sup>11</sup> P. Gaubert: *Bull. Soc. Fr. Min.*, XXXIII, 335 (1910), for paraffin with F. =  $44^\circ$ .

<sup>12</sup> B. Hubbard: *Am. Mineral.*, XXX, 645 (1945).

<sup>13</sup> G. Cesàro: *Ann. Soc. Géol. Belg.*, XVIII, p. lxxxviii (1891).

<sup>14</sup> P. Gaubert: *Bull. Soc. Fr. Min.*, XXXIII, 335 (1910).

orthorhombic with <sup>15</sup>  $(+ )2E = 10^\circ \pm$ ,  $r < v$  weak to distinct.  $C_{39}H_{80}$ , with <sup>16</sup>  $F. = 79^\circ C.$ , has  $(+ )2V = 0^\circ - 33^\circ$ ,  $r < v$  strong,  $N_X = 1.518$ ,  $N_Y = 1.523$ ,  $N_Z = 1.588$ ,  $N_Z - N_X = 0.070$ . On recrystallization the fibers have negative elongation. Also yellow with <sup>17</sup>  $(+ )2E = 48^\circ - 49^\circ$ ,  $N_X < 1.519$ ,  $N_Z > 1.519$ ,  $N_Z - N_X =$  weak. (This resembles ozocerite.) Found in scales in dolomite in Slovakia; also in coal.

**Curtisite** ( $C_{24}H_{18}$ ) is probably orthorhombic <sup>18</sup> with perfect 001 and poor 100 cleavages.  $H. < 2$ .  $G. = 1.236$ .  $F. = 350^\circ C.$  Soluble in hot benzol. The optic plane is 010;  $Z = c$ .  $(+ )2V = 83^\circ 30'$ ,  $r > v$  weak.  $N_X = 1.577$ ,  $N_Y = 1.734$ ,  $N_Z = 2.07$ ,  $N_Z - N_X = 0.513$ . Color greenish yellow with  $X =$  pale yellow to colorless,  $Y =$  yellow,  $Z =$  yellow and  $X < Y < Z$ . Found about hot springs in California.

**Flagstaffite** ( $H_{20}C_{10}O_2 \cdot H_2O$ ) or *terpin hydrate* is orthorhombic <sup>19</sup> with  $a:b:c = 0.807:1:0.476$ . Crystals prismatic with poor 110 cleavage. Very soft.  $G. = 1.09$ .  $F. = 116^\circ C.$  Soluble in warm alcohol. The optic plane is 010;  $Z = a$ .  $(+ )2V = 77^\circ$ ,  $r > v$  weak.  $N_X = 1.505$  Na,  $N_Y = 1.512$ ,  $N_Z = 1.524$ ,  $N_Z - N_X = 0.019$ . Colorless. Found in cracks in a log in Arizona.

**Hoelite** (*anthraquinone*,  $C_{14}H_8O_2$ ) is orthorhombic dipyramidal <sup>20</sup> with  $a:b:c = 0.80:1:0.16$ . Space group  $Pmmn$ ;  $a$  19.7,  $b$  24.5,  $c$  3.95 Å. U.C. 8. Crystals prismatic with poor 100 and 001 cleavages.  $G. = 1.43$ .  $F. = 273^\circ C.$  The optic plane is 100;  $X = c$ .  $2V =$  small,  $N_X = 1.57$ ,  $N_Y = 1.75$  ca,  $N_Z - N_X = 0.3$  ca. Colorless. Formed from vapors from burning coal.

**Fichtelite** <sup>21</sup> ( $C_{19}H_{34}$ ) is monoclinic sphenoidal with  $a:b:c = 1.435:1:1.758$ ,  $\beta = 127^\circ 05'$ . Space group  $P2_1$ ;  $a$  10.69,  $b$  7.45,  $c$  13.10 Å. U.C. 2. Crystals basal tablets or elongated parallel to  $b$ . Perfect 001 and distinct  $\bar{1}01$  cleavages. Twinning on 001.  $H. = 1$ .  $G. = 1.045$ .  $F. = 46^\circ C.$  Soluble in ether. The optic plane is 010;  $Z \wedge c$  <sup>22</sup>  $= -13^\circ$ .  $(- )2V = 87^\circ 20'$ ,  $N_X = 1.544$  (calc.),  $N_Y = 1.572$ ,  $N_Z = 1.60$ ,  $N_Z - N_X = 0.055$  ca. Color white. Found as scales in wood and peat, as in Bavaria and England.

**Hartite** ( $C_{18}H_{30}$ ) is triclinic pedial <sup>23</sup> with  $a:b:c = 0.548:1:0.360$ ,  $\alpha = 93^\circ 44'$ ,  $\beta = 100^\circ 26'$ ,  $\gamma = 80^\circ 31'$ . Crystals {010} tablets with  $G. = 1.04$ .  $F. = 74^\circ C.$  Soluble in alcohol. The acute bisectrix  $Z$  is nearly normal to 010 and the optic plane makes an angle of  $3^\circ$  with  $\bar{1}\bar{1}\bar{1}$  in 010.  $(+ )2E = 154^\circ$ . Indices unknown. Found on lignite, as near Vienna and in Styria, Austria.

**Succinite** is a fossil resin or amber.  $H. = 2-2.5$ .  $G. = 1.06-1.075$ .  $F. = 250^\circ - 300^\circ C.$  Partly soluble in alcohol. Isotropic with  $N = 1.53$  (Dahms <sup>24</sup>); 1.543

<sup>15</sup> A. Des Cloizeaux: *Manuel Minéral.*, II, 38 (1874).

<sup>16</sup> I. Morozewicz: *Bull. Acad. Sci. Cracovie*, 1908, 1067.

<sup>17</sup> F. Slavik: *Min. Abst.*, VII, 107 (1938).

<sup>18</sup> F. E. Wright and E. T. Allen: *Am. Mineral.*, XI, 67 (1926); XV, 169 (1930).

<sup>19</sup> F. N. Guild: *Am. Mineral.*, V, 169 (1920); VI, 133 (1921).  $a$  and  $b$  interchanged to make  $a < b$ .

<sup>20</sup> I. Oftedal: *Min. Abst.*, II, 10 (1923). E. Hertel and G. H. Römer: *Zeit. phys. Chem.*, XI, 90 (1930); *Strukturber.*, III, 794 (1937).

<sup>21</sup> D. Crowfoot: *Jour. Chem. Soc. London*, 1938, 1241.

<sup>22</sup> F. Plzak and V. Rosicky: *Zeit. Krist.*, XLIV, 332 (1908); A. Rosati: *Zeit. Krist.*, L, 126 (1911).

<sup>23</sup> F. Machatschki: *Zeit. Krist.*, LX, 130 (1924).  $a$  and  $b$  interchanged to make  $b > a$ . Also called josenite (Ger. *Josen*).

<sup>24</sup> P. Dahms: *Schr. Nat. Gesell. Danzig*, XI, pt. 4, 25 (1906).

(Larsen <sup>25</sup>). Color amber yellow. By weathering, G. increases to 1.09 and N decreases to 1.51 or even 1.49. It is of vegetable origin. Found in Prussia, England and Mexico.

**Coal.** The carbon in coal is not diamond nor graphite, although anthracite is nearly pure carbon. Recent work has shown that the refractive index of vitrain is a good indication of the quality of the coal. Thus, Fisher <sup>26</sup> found that vitrain of bituminous coal has  $N = 1.76$  and that of semibituminous coal has  $N = 1.87$ . Also McCabe and Quirke <sup>27</sup> found the results as tabulated.

Material	Source	Fixed Carbon	Volatile Matter	Moisture	B.t.u. <sup>28</sup>	Ref. Index
1. Woody lignite	Hernando, Miss.	31.2	32.9	32.1	7048	1.632
2. Vitrain	Lafayette, Colo.	46.4	29.5	21.7	10265	1.703
3. Vitrain	Pershing, Iowa	45.6	34.4	18.7	11540	1.715
4. Vitrain	Middle Grove, Ill.	49.74	33.61	16.0	12188	1.723
5. Vitrain	Roanoke, Ill.	49.6	33.5	15.7	12303	1.723
6. Vitrain	Booneville, Ind.	49.50	40.60	9.18	13240	1.750
7. Vitrain	Harrisburg, Ill.	58.0	35.7	3.7	14160	1.768
8. Vitrain	Gibsonia, Ill.	55.9	40.1	2.3	14769	1.768
9. Vitrain	Hartshorne, Okla.	73.28	23.92	0.56	15680	1.795

Cannon and George <sup>29</sup> found that lignite and cannel coal are optically isotropic, but vitrain from coals containing more than about 68% fixed carbon is anisotropic, the index for light vibrating normal to the bedding increasing from 1.80 (at 68% of fixed carbon) to 1.91 (at 86% C) and then remaining nearly constant,<sup>30</sup> while the

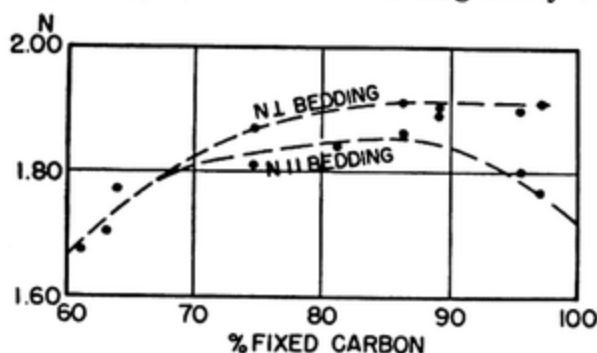


FIG. 86. Refractive index of coal [Data of C. G. Cannon and W. H. George: *Nature*, CLI, 53 (1943).]

index for light vibrating parallel with the bedding increases from 1.80 at 68% C to 1.85 at about 85% C and then decreases to 1.77 at 97% C. See Fig. 86. This results in a rather steady increase in the birefringence from 0 at 68% C to 0.14 at 97% C. But some coking coals are isotropic<sup>31</sup> with an index as high as about 1.87; such coal has a dispersion  $N_{5000} - N_{7000}$  of about 0.05.

<sup>25</sup> E. S. Larsen: *U. S. Geol. Surv. Bull.* 679 (1921) and 848 (1934).

<sup>26</sup> D. J. Fisher: *Am. Mineral.*, XIX, 133 (1934).

<sup>27</sup> L. C. McCabe and T. T. Quirke: *Am. Inst. Min. Eng. Tech. Pub.*, 791 (1937).

<sup>28</sup> Calculated on moist mineral-matter-free basis.

<sup>29</sup> C. G. Cannon and W. H. George: *Nature*, CLI, 53 (1943).

<sup>30</sup>  $N \perp$  bedding reaches 1.93 in some Welsh anthracite coal. See C. G. Cannon and W. H. George: *Nature*, CLI, 225 (1943).

<sup>31</sup> C. G. Cannon and W. H. George: *Nature*, CLI, 225 (1943).

## VII. BORATES

X-ray studies have shown that in borates each boron atom is surrounded by three oxygen atoms, all four atoms being in one plane, as with the oxygen atoms about each carbon atom in carbonates. A simple example of this kind is found in jeremejevite— $\text{AlBO}_3$ . If two such  $\text{BO}_3$  groups share one oxygen atom the formula includes  $\text{B}_2\text{O}_5$ , but this case is not known in any mineral. If each  $\text{BO}_3$  group shares two of its oxygen atoms with another  $\text{BO}_3$  group the formula must contain  $\text{BO}_2$ , or a multiple thereof, as in pinnoite— $\text{MgB}_2\text{O}_4 \cdot 3\text{H}_2\text{O}$ . If some of the  $\text{BO}_3$  groups share two oxygen atoms and others share all three oxygen atoms with other  $\text{BO}_3$  groups formulas result containing less than twice as many oxygen atoms as the number of boron atoms. Good examples are such borates as colemanite— $\text{Ca}_2\text{B}_6\text{O}_{11} \cdot 5\text{H}_2\text{O}$ , and borax— $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$ . But the exact arrangement of the  $\text{BO}_3$  groups in many borates is still unknown; therefore the correct placing of some minerals in the following classification is still uncertain.

1. Borates with type formula  $\approx A_m(\text{BX}_3)_n$ .
2. Borates with type formula  $\approx A_m(\text{BX}_2)_n$ .
3. Borates with type formula  $\approx A_mB_6X_{11}$ .
4. Borates with type formula  $\approx A_mB_4X_7$ .

### 1. Borates with type formula $\approx A_m(\text{BX}_3)_n$

**Rhodizite**  $[(\text{Na},\text{K})_2\text{Li}_4\text{Al}_4\text{Be}_3\text{B}_{10}\text{O}_{27}]$  is isometric hextetrahedral;<sup>1</sup> space group  $P\bar{4}3m$ ;  $a$  7.30 Å. U.C. 1. Indistinct 111 cleavage.  $H. = 8$ .  $G. = 3.4$ .  $F. = 7$ . Insoluble in acids. Often faintly anisotropic with  $N = 1.6935$  Na. Also  $N_z - N_x = 0.0017$ . Heat does not make crystals isotropic. Color white or yellow. Found in pegmatite, as in Madagascar.

**Teepleite**  $(\text{Na}_4\text{B}_2\text{O}_4\text{Cl}_2 \cdot 4\text{H}_2\text{O})$  is ditetragonal dipyramidal<sup>2</sup> with  $c/a = 0.669$ . Space group  $P4/nmm$ ;  $a$  7.27,  $c$  4.84 Å. Crystals basal plates with  $\{101\}$ . Conchoidal fracture.  $H. = 3-3.5$ .  $G. = 2.076$ . Soluble in water. Uniaxial negative

<sup>1</sup> H. Strunz: *Naturw.*, XXVI, 217 (1938); XXXI, 68 (1943).

<sup>2</sup> W. A. Gale, W. F. Foshag and M. Vonsen: *Am. Mineral.*, XXIV, 48 (1939).

with  $N_O = 1.519$ ,  $N_E = 1.503$ ,  $N_O - N_E = 0.016$ . Colorless. Found at Borax Lake, California.

**Nordenskiöldite** ( $\text{CaSnB}_2\text{O}_6$ ) is rhombohedral with  $c/a = 0.822$ . Structure like that of dolomite.<sup>3</sup> Space group  $R\bar{3}$ ;  $a$  6.00 Å. U.C. 1. Crystals basal plates with perfect 0001 cleavage. H. = 5.5–6. G. = 4.20. F. = 7, but sinters. Partly soluble in HCl. Uniaxial negative<sup>4</sup> with  $N_O = 1.778$ ,  $N_E = 1.660$ ,  $N_O - N_E = 0.118$ . Color sulfur yellow. Found in pegmatite, as in Norway.

**Jeremejevit** or **Eremeyevite** ( $\text{AlBO}_3$ ) is hexagonal dipyramidal with  $c/a = 0.955$ . Space group<sup>5</sup>  $C6_3/m$ ;  $a$  8.57,  $c$  8.17 Å. U.C. 12. Crystals prismatic with complex twinning of biaxial and uniaxial parts. H. = 6.5. G. = 3.3. F. = 7. Insoluble in acids. Uniaxial negative to biaxial negative with  $2E = 65^\circ$ ,  $r > v$ . The optic plane is at  $30^\circ$  to hexagonal edges of basal section. The optic angle varies with pressure.  $N_O = 1.64$ ,  $N_O - N_E = \text{moderate (?)}$ . Colorless. Found in Siberia.

**Fluorborite** [ $\text{Mg}_3(\text{F},\text{OH})_3\text{BO}_3$ ] is hexagonal with H. = 3.5. G. =  $2.9 \pm$ . Soluble in  $\text{H}_2\text{SO}_4$ . Uniaxial negative with<sup>6</sup>  $N_O = 1.50$ – $1.58$ ,  $N_E = 1.49$ – $1.54$ ,  $N_O - N_E = 0.015$ – $0.05$ . See Fig. 87. Colorless. Found at Franklin, New Jersey, etc.

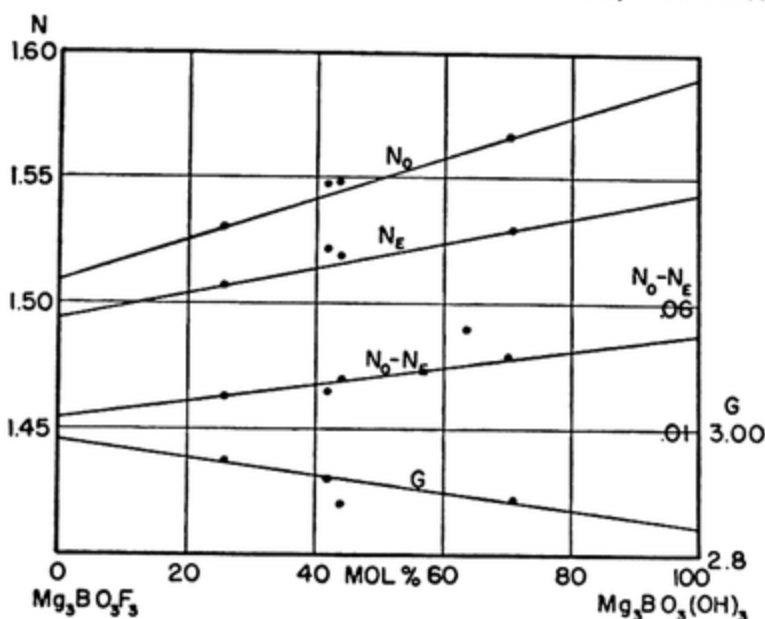


FIG. 87. Properties of fluorborite. Modified from W. T. Schaller: *Am. Mineral*, XXVII, 467 (1942).

**Ludwigite** [ $(\text{Mg},\text{Fe})_2\text{O}_2\text{Fe}'''\text{BO}_3$ ] is orthorhombic with  $a:b:c = 0.988:1:?$ . Crystals prismatic fibers. H. = 5. G. = 3.6 (with very little Fe) to 4.3. F. = 4. Soluble in HCl. Positive elongation. (+)2V = very small (but 2E may =  $40^\circ$ ),  $r > v$  strong to extreme.  $N_X = 1.84$  ca.,  $N_Y = 1.85$  ca.,  $N_Z = 1.98$  ca.,  $N_Z - N_X = 0.14$  ca. Color dark green with X and Y = deep olive green, Z = brown.<sup>7</sup> In ferrous ludwigite as much as one-fourth of the magnesium may be replaced by ferrous iron; then  $N_X = 1.85$  ca.,  $N_Y = 1.85$  ca.,  $N_Z = 2.02$  ca.,  $N_Z - N_X =$

<sup>3</sup> P. Ramdohr and W. Ehrenberg: *N. Jahrb. Min.*, Bl. Bd. LXIX, 1 (1935).

<sup>4</sup> P. Ramdohr: *N. Jahrb. Min.*, Bl. Bd. LXVII, 288 (1934).

<sup>5</sup> H. Strunz: *Naturw.*, XXVI, 217 (1938). See also *Cent. Min.*, 1934A, 348.

<sup>6</sup> W. T. Schaller: *Am. Mineral.*, XXVII, 467 (1942).

<sup>7</sup> A. Knopf: *Am. Mineral.*, XXVII, 824 (1942).



0.17 *ca.* Color blackish green with X and Y greenish, Z reddish brown, and nearly opaque in all directions. Ludwigite may alter to limonite. Found in crystalline limestone at Philipsburg, Montana, etc.

**Pinakiolite** ( $Mg_2O_2Mn''BO_3?$ ) is orthorhombic with  $a:b:c = 0.834:1:0.588$ . Crystals {010} tablets; twinning common on 011; distinct 010 cleavage.  $H. = 6$ .  $G. = 3.88$ .  $F. = 5$ . Soluble in HCl. The optic plane is 001;  $X = b$ .  $(- )2V = 32^\circ$ ,  $r < v(?)$ .  $N_X = 1.908$ ,  $N_Y = 2.05$ ,  $N_Z = 2.065$ ,  $N_Z - N_X = 0.067$ . Color black; reddish brown in section with  $Y > X > Z$ . Found in granular dolomite at Långban, Sweden.

**Hambergite** [ $Be_2(OH)BO_3$ ] is orthorhombic dipyramidal with  $a:b:c = 0.799:1:0.363$ . Space group  $Pbca$ ;  $a$  9.73,  $b$  12.18,  $c$  4.42 Å. U.C. 8. Crystals prismatic, vertically striated. Perfect 010 and good 100 cleavages.  $H. = 7.5$ .  $G. = 2.35$ .  $F. = 7$ . Insoluble except in HF. The optic plane is 010;  $X = a$ .  $(+ )2V = 87^\circ 7'$ ,  $r < v$  distinct.  $N_X = 1.559$ ,  $N_Y = 1.591$ ,  $N_Z = 1.631$ ,  $N_Z - N_X = 0.072$ ;  $N_X = 1.553$ ,  $N_Y = 1.586$ ,  $N_Z = 1.627$ ,  $N_Z - N_X = 0.074$ ;  $(+ )2V = 87^\circ 30'$ ,  $N_X = 1.540$ ,  $N_Y = 1.58$ ,  $N_Z = 1.615$ ,  $N_Z - N_X = 0.075$ .<sup>11</sup> Dispersion  $G - B$  for  $N_Z = 0.017$ . Color white. Found in pegmatite in Norway and Madagascar.

**Roweite** ( $H_2MnCaB_2O_6$ ) is orthorhombic<sup>13</sup> with  $a:b:c = 0.916:1:0.735$ .  $a$  8.27,  $b$  9.01,  $c$  6.62 Å. U.C. 4. Crystals show {010}, {100}, and {101}. Poor 101 cleavage.  $H. = 5$ .  $G. = 2.92$ .  $F. = 1$ . Soluble in dilute HCl. The optic plane is 001;  $X = a$ .  $(- )2V = 15^\circ$ ,  $r < v$  strong.  $N_X = 1.648$ ,  $N_Y = 1.660$ ,  $N_Z = 1.663$ ,  $N_Z - N_X = 0.015$ . Found at Franklin, New Jersey.

**Warwickite** [ $(Mg,Fe)TiO_2B_2O_6$ ] is orthorhombic with  $a:b:c = 0.977:1:?$ . Crystals prismatic with perfect 100 cleavage.  $H. = 3-4$ .  $G. = 3.4$ .  $F. = 5.5$ . Decomposed by  $H_2SO_4$ . The optic plane is 010;  $X = c$ . See Fig. 88.  $(+ )2V = 59^\circ$  (variable),  $N_X = 1.806$ ,  $N_Y = 1.809$ ,  $N_Z = 1.830$ ,  $N_Z - N_X = 0.024$ . Color dark brownish to dull black with  $X =$  clear yellowish brown,  $Y =$  reddish brown,  $Z =$  brown and  $X > Y > Z$ . Found in granular limestone near Edenville, New York.

**Szaibelyite** [ $H_2(Mg,Mn,Zn)_2B_2O_6$ ] is orthorhombic, usually lath-shaped or fibrous parallel to  $c$ .  $H. = 3-4$ .  $G. = 2.6-3.3$ . Fuses. Slowly soluble in HCl.  $X = c$ .  $Y$  normal to laths; (Ellsworth<sup>14</sup>);  $Z$  normal to laths (Schaller<sup>6</sup>).  $(- )2V =$  small.  $N_X = 1.575-1.675$ ,  $N_Y = 1.620-1.735$ ,  $N_Z = 1.65-1.74$ ,  $N_Z - N_X = 0.075-0.055$ . See Fig. 89. A variety with Mn dominant is called *sussexite*; with Mg dominant it has been called *camsselite*.<sup>15</sup> Found in limestone and in ore deposits as in Hungary and at Franklin, New Jersey.

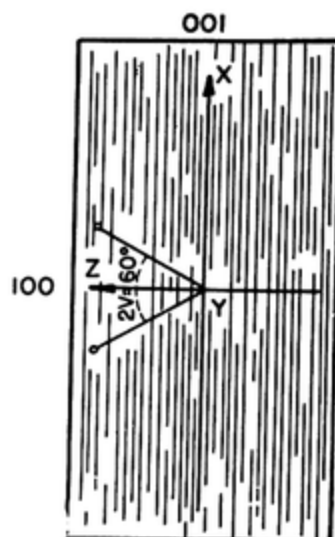


FIG. 88. The optic orientation of warwickite.

<sup>8</sup> W. H. Zachariasen: *Zeit. Krist.*, LXXVI, 289 (1931).

<sup>9</sup> W. C. Broegger: *Zeit. Krist.*, XVI, 65 (1890).

<sup>10</sup> A. Lacroix: *Minéral. France*, IV, 347 (1910).

<sup>11</sup> W. J. Sokolow: *Zeit. Krist.*, LII, 633 (1913).

<sup>12</sup> C. J. Payne: *Min. Abst.*, VII, 518 (1940).

<sup>13</sup> H. Berman and F. A. Gonyer: *Am. Mineral.*, XXII, 301 (1937).

<sup>14</sup> H. V. Ellsworth and E. Poitevin: *Trans. Roy. Soc. Canada*, XV, 1 (1921).

<sup>15</sup> M. N. Godlevsky: *Mem. Soc. Russe Mineral.*, LXVI, 315 (1937).

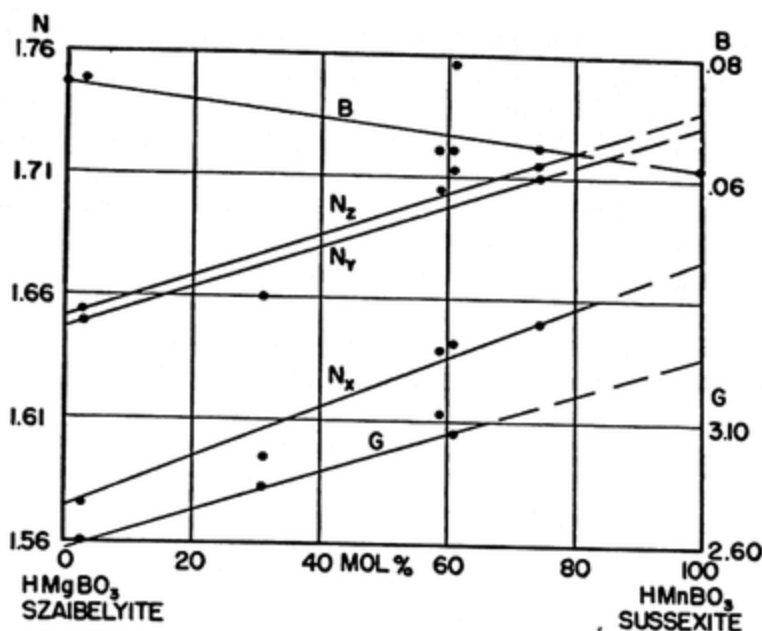


FIG. 89. Properties of the szaibelyite-sussexite series. Modified from W. T. Schaller: *Am. Mineral.*, XXVII, 467 (1942).

**Kotoite** ( $\text{Mg}_3\text{B}_2\text{O}_6$ ) is orthorhombic<sup>16</sup> with  $a:b:c = 0.642:1:0.536$ .  $a$  5.41,  $b$  8.42,  $c$  4.51 Å. Natural crystals much rounded, with perfect 110 cleavage at an angle of  $65^\circ 20'$ ; also 101 parting. Lamellar twinning.  $H. = 6.5$ .  $G. = 3.06\text{--}3.11$ .  $F. = 1340\text{--}1350^\circ\text{C}$ . The optic plane is 010;  $Z = c$ .  $(+ )2V = 21^\circ$ ,  $r > v$ ,  $N_X = 1.652$ ,  $N_Y = 1.653$ ,  $N_Z = 1.673$ ,  $N_Z - N_X = 0.021$ . Colorless. Found as a granular constituent of dolomitic marble associated with forsterite, clinohumite, spinel, ludwigite, etc. in Korea. Alters under hydrothermal conditions to szaibelyite.

## 2. Borates with type formula $\approx \text{A}_m(\text{BX}_2)_n$

**Pinnoite** ( $\text{MgB}_2\text{O}_4 \cdot 3\text{H}_2\text{O}$ ) is tetragonal<sup>17</sup> with  $c/a = 1.075$ . Space group  $P4_2/m$  or  $P4_2$ .  $a$  7.617,  $c$  8.190 Å. U.C. 4. Crystals prismatic, rare.  $H. = 3\text{--}4$ .  $G. = 2.29$ .  $F. = 3$ . Soluble in acid. Uniaxial positive<sup>18</sup> with  $N_O = 1.565$ ,  $N_E = 1.575$ ,  $N_E - N_O = 0.010$ . Color yellow. Found with boracite at Stassfurt, Germany.

**Bandylite** ( $\text{CuClBO}_2 \cdot 2\text{H}_2\text{O}$ ) is ditetragonal dipyramidal<sup>19</sup> with  $c = 0.907$ . Space group  $P4/nmm$ ;  $a$  6.13,  $c$  5.54 Å. U.C. 4. Crystals are basal tablets with perfect basal cleavage.  $H. = 2.5$ .  $G. = 2.81$ . Uniaxial negative with  $N_O = 1.691$ ,  $N_E = 1.641$ ,  $N_O - N_E = 0.050$ . Color deep blue with  $O =$  deep cendre blue (Ridgway),  $E =$  pale greenish yellow. Found at Calama, Chile.

<sup>16</sup> T. Watanabe: *Tsch. Min. Pet. Mit.*, L, 441 (1939), LI, 162 (1939); *N. Jahrb. Min.*, 1939A, 52; *Fort. Min. Krist. Vet.*, XXIII (1939).

<sup>17</sup> H. P. Stadler: *Mineral. Mag.*, XXVIII, 26 (1947). Classification of pinnoite as a metaborate is doubtful.

<sup>18</sup> H. E. Boeke: *Cent. Mineral.*, 1910, 531.

<sup>19</sup> C. Palache and W. F. Foshag: *Am. Mineral.*, XXIII, 85 (1938).

**BORACITE**

## ORTHORHOMBIC PYRAMIDAL



$$a:b:c = 0.70:1:1$$

STRUC. Space group  $^{20}$  *Cmm* or *Cmc*;  $a$  12.07,  $b$  17.07,  $c$  17.07 Å. U.C. 8. Pseudo-isometric.

PHYS. CHAR. Crystals cubic, tetrahedral, or dodecahedral; twinning on 111 rare; a fibrous variety is known as *stassfurtite*. 111 cleavage in traces.  $H. = 7$ .  $G. = 2.95$ .  $F. = 2$  with intumescence. Soluble in HCl.

OPT. PROP. The isometric phase is stable above  $265^\circ C.$ , and below that the external form is retained by complex twinning of the orthorhombic unit, each dodecahedral face being a twinning plane in one type, each face being normal to the bisectrix, the optic plane being parallel to the longer diagonal of the face. Other twinning often present.  $(+)2V = 83^\circ$  ca.  $N_X = 1.662$ ,  $N_Y = 1.663$  Li, 1.667 Na, 1.675 blue,  $N_Z = 1.673$ ,  $N_Z - N_X = 0.011$ . Again:  $^{21}$   $N_X = 1.658$ ,  $N_Y = 1.662$ ,  $N_Z = 1.668$ ,  $N_Z - N_X = 0.010$ . Color white. A greenish variety contains iron and inverts at  $285^\circ C.$  *Stassfurtite* has parallel extinction and positive elongation.

INVER. A reversible inversion occurs at  $265^\circ C.$  to an isometric phase in the space group  $F\bar{4}3m$  with  $a$  12.1. U.C. 4.

ALTER. Boracite becomes cloudy by hydration.

OCCUR. It is found in beds with gypsum, anhydrite, and halite.

DIAG. The optic properties with the form are quite distinctive.

**Veatchite**  $^{22}$  ( $H_{10}Sr_3B_{16}O_{32}?$ ) is monoclinic  $^{23}$  with  $a:b:c = 0.163:1:0.998$ ,  $\beta = 121^\circ 2'$ .  $a$  6.72,  $b$  41.26,  $c$  41.20 Å. U.C. 16. Fibrous or platy with perfect 010 and poor 001 cleavages.  $H. = 2$ .  $G. = 2.58$ . The optic plane is 010;  $Z \wedge c = 38^\circ$ .  $(+)2V = 37^\circ$ ,  $r > v$  weak.  $N_X = 1.551$ ,  $N_Y = 1.553$ ,  $N_Z = 1.621$ ,  $N_Z - N_X = 0.070$ . Found in veins in limestone or shale in California.

**Howlite** ( $2CaSiO_3 \cdot H_6Ca_2B_{10}O_{20} \cdot 2H_2O?$ ) is monoclinic and tabular parallel to 100, elongated along  $c$  or  $b$ .  $H. = 3.5$ .  $G. = 2.58$ .  $F. = 2$ . Insoluble in HCl.  $X = b$ ;  $Z \wedge c = 44^\circ \pm$ .  $(-)2V = \text{large}$ .  $N_X = 1.586$ ,  $N_Y = 1.598$ ,  $N_Z = 1.605$ ,  $N_Z - N_X = 0.019$ . Color white. Found with *ulexite* in Nova Scotia and with borax in California.

**Probertite** ( $H_2NaCaB_5O_{10} \cdot 4H_2O?$ ) is monoclinic prismatic  $^{24}$  with  $a:b:c = 1.105:1:0.524$ ,  $\beta = 107^\circ 44'$ . Space group  $P2_1/n$ ;  $a$  13.86,  $b$  12.54,  $c$  6.61 Å. U.C. 2. Crystals long prismatic with perfect 110 cleavage.  $H. = 3.5$ .  $G. = 2.14$ .  $F. = 1$ .  $Y = b$ ;  $Z \wedge c = 12^\circ - 13^\circ$ .  $(-)2V = 73^\circ$ ,  $r > v$ .  $N_X = 1.515$ ,  $N_Y = 1.525$ ,  $N_Z = 1.544$ ,  $N_Z - N_X = 0.029$ . Again:  $N_X = 1.515$ ,  $N_Y = 1.520$ ,  $N_Z = 1.538$ ,  $N_Z - N_X = 0.023$ . Colorless. Found in borax deposits near Kramer, California.

**Larderellite** [ $H_8(NH_4)_2B_{10}O_{20} \cdot H_2O?$ ] is monoclinic in {100} tablets with perfect 001 cleavage. Plates rhombic with an angle of  $60^\circ$ . Cleavage rhombs are pseudo-

$^{20}$  M. Mehmél: *Zeit. Krist.*, LXXXVII, 239, and LXXXVIII, 1 (1934); also J. W. Gruner: *Am. Mineral.*, XIII, 481 (1928) and *Am. Jour. Sci.*, CCXVII, 453 (1929).

$^{21}$  E. M. Grippy and C. O. Harvey: *Mineral. Mag.*, XXVII, 51 (1944).

$^{22}$  G. Switzer: *Am. Mineral.*, XXIII, 409 (1938). G. Switzer and W. W. Brannock: *Am. Mineral.*, XXXV, 90 (1950).

$^{23}$  J. Murdock: *Am. Mineral.*, XXIV, 130 (1939).

$^{24}$  A. S. Eakle: *Am. Mineral.*, XIV, 427 (1929); later called *kramerite* by W. T. Schaller: *U. S. Geol. Surv. Prof. Paper* 158, 130 (1930). See also W. F. Foshag: *Am. Mineral.*, XVI, 338 (1931); W. H. Barnes: *Am. Mineral.*, XXXII, 684 (1947); XXXIV, 19 (1949).

hexagonal. Soft. F. = easy. Soluble in water.  $X = b$ .  $Y$  near  $a$ .  $Z \wedge c = 24^\circ$ .  $(+ )2V = 60^\circ \pm$ .  $N_X = 1.509$ ,  $N_Y = 1.52$  ca.,  $N_Z = 1.561$ ,  $N_Z - N_X = 0.052$  (Larsen<sup>25</sup>);  $N_X = 1.493$ ,  $N_Y = 1.509$ ,  $N_Z = 1.561$ ,  $N_Z - N_X = 0.068$  (Schaller<sup>26</sup>). Colorless. Found in Tuscan lagoons.

**Kaliborite**<sup>27</sup> ( $H_6KMg_2B_{11}O_{22} \cdot 6H_2O$ ?) is monoclinic with  $a:b:c = 1.291:1:1.757$ ,  $\beta = 122^\circ 19'$ . Crystals complex with perfect 100 and 001 cleavages.  $H. = 4.5$ .  $G. = 2.13$ .  $F. = 1$ . Soluble in acid. The optic plane and  $X$  are normal to 010;  $Z \wedge \perp 001 = +65^\circ$ .  $(+ )2V = 81^\circ$ ,  $N_X = 1.508$ ,  $N_Y = 1.5255$ ,  $N_Z = 1.550$ ,  $N_Z - N_X = 0.042$ . Color white. Found in salt deposits at Stassfurt, Germany.

**Ginorite** ( $H_{10}Ca_2B_{14}O_{28} \cdot 3H_2O$ ?) is probably monoclinic<sup>28</sup> with perfect 010 cleavage. The angle of 010 plates is  $78^\circ$ .  $H. = 3.5$ .  $G. = 2.09$ . The optic plane and  $Z$  are normal to 010;  $X \wedge$  elongation  $= 51^\circ$ .  $(+ )2V = 42^\circ$ ,  $N_X = 1.517$ ,  $N_Y = 1.524$  (calc.),  $N_Z = 1.577$ ,  $N_Z - N_X = 0.060$ . Colorless. Found with calcite in veins in sandstone.

**Ammonioborite**<sup>29</sup> [ $H_4(NH_4)_2B_{10}O_{20} \cdot H_2O$ ?] is probably triclinic (in indefinite crystals), since extinction measure on slight elongation varies from  $7^\circ$  to  $13^\circ$ .  $X$  near  $b$ .  $(+ )2V = 60^\circ \pm 10^\circ$ ,  $r < v$ .  $N_X = 1.470$ ,  $N_Y = 1.487$ ,  $N_Z = 1.540$ ,  $N_Z - N_X = 0.070$ . Colorless. Found with larderellite.

**Priceite** ( $H_2Ca_5B_{12}O_{24} \cdot 8H_2O$ ?) or *pandermite* is triclinic(?) or monoclinic with  $a:b:c = 0.551:1:?$ ,  $\beta = 110^\circ$  ca. Crystals minute rhombic plates of  $58^\circ$  angle. Perfect 001, distinct 110, and poor 010 cleavages.  $H. = 3$ .  $G. = 2.43$ . Soluble in HCl.  $X$  makes an angle of  $25^\circ$  with a normal to the plates. Extinction ( $X'$ ) on plates is at about  $14^\circ$  to the bisector of the acute angle (Larsen<sup>25</sup>). The optic plane is 010;  $X \wedge c = 20^\circ$ – $23^\circ$  (Linck<sup>30</sup>).  $(- )2V = 32^\circ$ ,  $r < v$  marked.  $N_X = 1.572$ ,  $N_Y = 1.591$ ,  $N_Z = 1.594$ ,  $N_Z - N_X = 0.022$ . Color white. Found in borate deposits in Turkey, Oregon, California, etc.

**Johachidolite**<sup>31</sup> ( $H_6Na_2Ca_3Al_4O_8F_5B_6O_{12}$ ?) is biaxial.  $H. = 6.5$ – $7$ .  $G. = 3.4$ . Colorless. Under ultraviolet rays it shows intense blue fluorescence.  $(+ )2V = 72^\circ$ , calc.  $N_X = 1.715$ ,  $N_Y = 1.720$ ,  $N_Z = 1.729$ ,  $N_Z - N_X = 0.014$ . Found in nepheline veins in limestone in Korea.

**Ulexite** ( $H_2NaCaB_5O_{10} \cdot 7H_2O$ ?) is triclinic pinacoidal with  $a:b:c = 0.686:1:0.519$ ,  $\alpha = 90^\circ 16'$ ,  $\beta = 109^\circ 8'$ ,  $\gamma = 105^\circ 7'$ . Space group<sup>32</sup>  $P\bar{1}$ ;  $a$  8.71,  $b$  12.72,  $c$  6.69 Å. U.C. 2. Vertical fibers form "cotton balls."  $H. = 2.5$ .  $G. = 1.96$ .  $F. = 1$  with intumescence. Soluble in acid. The optic plane and  $Z$  are nearly normal to 010;  $Y \wedge c = 4^\circ$ .  $(+ )2V = 78^\circ$ ,  $N_X = 1.496$ ,  $N_Y = 1.505$ ,  $N_Z = 1.519$ ,  $N_Z - N_X = 0.023$  (Godlevsky<sup>33</sup>). Again:  $Y \wedge c = 21^\circ 30'$ ,  $(+ )2V = 73^\circ$  (Murdoch<sup>32</sup>).

<sup>25</sup> E. S. Larsen: *U. S. Geol. Surv. Bull.* 679 (1921) and 848 (1934).

<sup>26</sup> W. T. Schaller: personal communication, Nov. 25, 1931; *Am. Mineral.*, XVIII, 485 (1933). Larsen's value of  $N_X$  is said to be too high.

<sup>27</sup> Also known as *hintzeite*. See M. N. Godlevsky: *Mem. Soc. Russe Min.*, LXVII, 2, 258 (1938).

<sup>28</sup> G. D'Achiardi: *Per. Mineral.*, V, 22 (1934); *Min. Abst.*, V, 484 (1934).

<sup>29</sup> W. T. Schaller: *Am. Mineral.*, XVIII, 480 (1933). See also G. D'Achiardi: *Min. Abst.*, VI, 153 (1935).

<sup>30</sup> G. Linck: *Cent. Mineral.*, 1923, 193.

<sup>31</sup> E. Iwasi and N. Saito: *Chem. Abst.*, XLI, 6173 (1947). Also *Min. Abst.*, X, 253 (1948); *Amer. Min.*, XXXIII, 98 (1933), *abst.*

<sup>32</sup> J. Murdoch: *Am. Mineral.*, XXV, 754 (1935).

<sup>33</sup> M. N. Godlevsky: *Min. Abst.*, VII, 122 (1938).

Also:  $Y \wedge c = 23^\circ$ ,  $(+)2V = \text{large}$ ,  $N_X = 1.491$ ,  $N_Y = 1.504$ ,  $N_Z = 1.521$ ,  $N_Z - N_X = 0.030$  (Larsen<sup>25</sup>). Colorless. Abundant in some borate deposits in California, etc.

**Lagonite** ( $\text{FeB}_3\text{O}_6 \cdot 1.5\text{H}_2\text{O}$ ?) is amorphous and probably a mixture. Soft and earthy. Isotropic with  $N = 1.64$  ca. Color ocher-yellow. Found in Tuscan lagoons.

### 3. Borates with type formula $\approx A_m B_6 X_{11}$

#### COLEMANITE

#### MONOCLINIC PRISMATIC



$$a:b:c = 0.777:1:0.542 \quad \beta = 110^\circ 9'$$

**STRUC.** Space group  $P2/m(?)$ .  $a$  8.61,  $b$  11.12,  $c$  6.10 Å (Dér<sup>34</sup>); U.C. 2;  $a$  8.72,  $b$  11.29,  $c$  6.06 (Nikolsky<sup>35</sup>).

**PHYS. CHAR.** Crystals short prismatic; massive; perfect 010 and distinct 001 cleavages.  $H. = 4$ .  $G. = 2.42$ .  $F. = 1.5$  with exfoliation. Soluble in hot HCl.

**OPT. PROP.** The optic plane and  $X$  are normal to 010;  $Z \wedge c = -83^\circ$ . See Fig. 90.  $(+)2V = 56^\circ$ ,  $r < v$  weak.  $N_X = 1.586$ ,  $N_Y = 1.592$ ,  $N_Z = 1.614$ ,  $N_Z - N_X = 0.028$ . Color white.

**OCCUR.** Found in arid regions, as in California.

**Inyoite** ( $\text{Ca}_2\text{B}_6\text{O}_{11} \cdot 13\text{H}_2\text{O}$ ) is monoclinic with  $a:b:c = 0.941:1:0.667$ ,  $\beta = 117^\circ 23'$  (Schaller<sup>36</sup>);  $0.883:1:0.695$ ,  $\beta = 114^\circ 1'$  (Poitevin-Ellsworth<sup>37</sup>). Crystals {001} tablets with good 001 cleavage.  $H. = 2$ .  $G. = 1.88$ . Decrepitates and fuses with much intumescence. Soluble in acid. The optic plane is 010;  $X \wedge c = -37^\circ$ .  $(-)2V = 70^\circ$  (Schaller<sup>36</sup>),  $80^\circ 33'$  (Poitevin<sup>37</sup>),  $r < v$  weak.  $N_X = 1.495$ ,  $N_Y = 1.51$ ,  $N_Z = 1.520$ ,  $N_Z - N_X = 0.025$ . Again:  $(-)2V = 84^\circ$  (Boldyreva<sup>38</sup>),  $N_X = 1.492$ ,  $N_Y = 1.505$ ,  $N_Z = 1.516$ ,  $N_Z - N_X = 0.024$ . Color white. Alters readily to meyerhofferite. Found in salt lake deposits, with colemanite, as in southwestern Siberia.

**Hydroboracite** ( $\text{CaMgB}_6\text{O}_{11} \cdot 6\text{H}_2\text{O}$ ) is monoclinic with  $a:b:c = 1.762:1:1.241$ ,  $\beta = 102^\circ 39'$ ; fibrous along  $c$ , with perfect 100 and 010 cleavages.  $H. = 2$ .  $G. = 2.0$ .  $F. = 2$  to clear glass. Soluble in acid. The optic plane is 010;  $X \wedge c = 31^\circ$ .  $(+)2V = \text{large}$ ,  $r < v$  moderate.  $N_X = 1.517$ ,  $N_Y = 1.534$ ,  $N_Z = 1.565$ ,  $N_Z - N_X = 0.048$  (Larsen<sup>23</sup>); again:  $38^\circ X \wedge c = 33^\circ$ ,  $(+)2V = 60^\circ$ ,  $N_X = 1.522$ ,  $N_Y = 1.534$ ,  $N_Z = 1.571$ ,  $N_Z - N_X = 0.049$ . Color white. Found in salt lake deposits, as near Inder Lake, Siberia.

**Inderborite** ( $\text{CaMgB}_6\text{O}_{11} \cdot \text{H}_2\text{O}$ ) is monoclinic<sup>39</sup> with  $a:b:c = 1.635:1:1.317$ ,  $\beta = 90^\circ 48'$ . Crystals show {100}, {001}, {110}, {221}, etc. Distinct 100 cleavage.

<sup>34</sup> Z. Dér: *Min. Abst.*, VIII, 289 (1942).

<sup>35</sup> V. A. Nikolsky: *Min. Abst.*, IX, 44 (1944).

<sup>36</sup> W. T. Schaller: *U. S. Geol. Surv. Bull.* 610, 35 (1916).

<sup>37</sup> E. Poitevin: *Canada Geol. Surv. Bull.* 32, 1921.

<sup>38</sup> A. M. Boldyreva: *Min. Abst.*, VI, 336 (1936). See also G. B. Boky: *Min. Abst.*, VII, 123 (1938).

<sup>39</sup> G. S. Gorschkov: *C. R. Acad. Sci. U.R.S.S.*, XXXIII, 254 (1941). *Min. Abst.*, VIII, 341 (1943). N. Y. Ikornikova and M. N. Godlevsky: *loc. cit.*, p. 257, called the same mineral *metahydroboracite*.

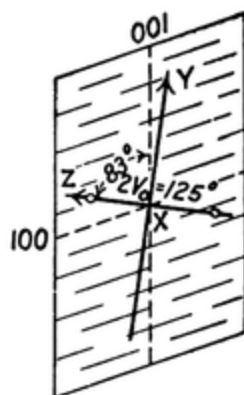


FIG. 90. The optic orientation of colemanite.



H. = 3 ca. G. = 1.93; 2.0. The optic plane and Z are normal to 010;  $X \wedge c = 1^\circ - 2^\circ$ .  $(- )2V = 80^\circ$  ca.  $N_X = 1.483$ ,  $N_Y = 1.512$ ,  $N_Z = 1.530$ ,  $N_Z - N_X = 0.047$ . Also:  $N_X = 1.496$ ,  $N_Y = 1.521$ ,  $N_Z = 1.538-1.544$ ,  $N_Z - N_X = 0.042-0.048$ . Color white; vitreous luster. Found in borate deposits near Inder Lake, Siberia.

**Kurnakovite** ( $Mg_2B_6O_{11} \cdot 13H_2O$ ) is probably monoclinic <sup>40</sup> with poor 010 cleavage. H. = 3. G. = 1.85. Fuses to an enamel. Soluble in acids. One optic axis is nearly normal to 001.  $(- )2V = 80^\circ$ ,  $N_X = 1.489$ ,  $N_Y = 1.510$ ,  $N_Z = 1.525$ ,  $N_Z - N_X = 0.036$ . Found at Inder Lake, Siberia.

**Hilgardite** [ $Ca_3Cl_4(B_6O_{11})_3 \cdot 4H_2O$ ] is monoclinic domatic with <sup>41</sup>  $a:b:c = 1.027:1:0.559$ ,  $\beta = 90^\circ 0'$ . Space group  $Pc$  or  $Pm$ ;  $a$  11.35,  $b$  11.12,  $c$  6.20 Å. U.C. 1. Crystals {010} tablets with {111},  $\{\bar{1}10\}$ , etc. Perfect 010 and 100 cleavages. H. = 5. G. = 2.71. The optic plane is 010;  $Z \wedge c = 1.5^\circ$ .  $(+ )2V = 35^\circ$ ,  $r > v$ ,  $N_X = 1.630$ ,  $N_Y = 1.636$ ,  $N_Z = 1.664$ ,  $N_Z - N_X = 0.034$ . Found in the insoluble residue from a brine well in Louisiana.

**Parahilgardite** [ $Ca_8(B_6O_{11})_3Cl_4 \cdot 4H_2O$ ] is triclinic pedial <sup>42</sup> with  $a:b:c = 0.5045:1:0.2783$ ,  $\alpha = 90^\circ 0'$ ,  $\beta = 90^\circ 0'$ ,  $\gamma = 91^\circ 12'$ . Space group  $P1$ ;  $a$  11.24,  $b$  22.28,  $c$  6.20 Å. U.C. 2. Crystals found only in pairs attached to the negative end of the  $a$  axis of a hilgardite crystal. Crystals show {010}, {121}, {321}, etc. Perfect 010 and 100 cleavages. H. = 5. G. = 2.71.  $X \wedge a = 20^\circ$ ;  $Z = c$  nearly.  $(+ )2V = 35^\circ$ ,  $r > v$ .  $N_X = 1.630$ ,  $N_Y = 1.636$ ,  $N_Z = 1.664$ ,  $N_Z - N_X = 0.034$ . Colorless. Differs from hilgardite in having an extinction angle of  $20^\circ$  in 001. Found in the Choctaw salt dome, Louisiana.

**Inderite** ( $Mg_2B_6O_{11} \cdot 15H_2O$ ) is triclinic pinacoidal <sup>43</sup> with  $a:b:c = 0.768:1:0.604$ ,  $\alpha = 96^\circ 57'$ ,  $\beta = 106^\circ 28'$ ,  $\gamma = 106^\circ 3'$ . Space group  $P\bar{1}(?)$ ;  $a$  8.14,  $b$  10.47,  $c$  6.33 Å. U.C. 1. Crystals prismatic or 010 tablets. Good 010 and  $1\bar{1}0$  cleavages at an angle of  $66^\circ 20'$ . H. = 3. G. = 1.86.  $X$  is near  $b$ ;  $Z \wedge c = -22^\circ$ ;  $(- )2V = 63^\circ$ ,  $r > v$  weak.  $N_X = 1.488$ ,  $N_Y = 1.508$ ,  $N_Z = 1.515$ ,  $N_Z - N_X = 0.027$  (Heinrich <sup>43</sup>).  $Z \wedge c = 5^\circ-7^\circ$ ,  $(- )2V =$  large,  $N_Y = 1.488$ ,  $N_Z = 1.505$  (Boky <sup>44</sup>). Colorless. Found in borate deposits in Russia and California.

**Meyerhofferite** ( $Ca_2B_6O_{11} \cdot 7H_2O$ ) is triclinic pinacoidal <sup>45</sup> with  $a:b:c = 0.792:1:0.778$ ,  $\alpha = 91^\circ 0'$ ,  $\beta = 101^\circ 31'$ ,  $\gamma = 86^\circ 55'$ . Space group  $P\bar{1}$ ;  $a$  6.60,  $b$  8.33,  $c$  6.48 Å. U.C. 1. Crystals vertical prisms or {100} tablets with perfect 010 cleavage. H. = 2. G. = 2.12. F. = easy with intumescence. Axis  $Z$  makes a moderate angle with a normal to  $\bar{1}00$ . Extinction on  $\bar{1}00$  is  $Z' \wedge c = 25^\circ$ ; extinction on 010 is  $X' \wedge c = 33^\circ$ .  $(- )2V = 78^\circ$ ,  $r > v$  weak.  $N_X = 1.500$ ,  $N_Y = 1.535$ ,  $N_Z = 1.560$ ,  $N_Z - N_X = 0.060$ . Colorless. A dehydration product of inyoite, found in Inyo County, California.

#### 4. Borates with type formula $\approx A_mB_4X_7$

**Bechilite** ( $CaB_4O_7 \cdot 4H_2O$ ) is a doubtful species.<sup>25</sup> A sample so labeled from Chile contains a negative uniaxial mineral with  $N_O = 1.531$ ,  $N_E = 1.510$ ,  $N_O - N_E$

<sup>40</sup> M. N. Godlevsky: *C. R. Acad. Sci. U.R.S.S.*, XXVIII, No. 7, 638 (1940).

<sup>41</sup> C. S. Hurlbut and R. E. Taylor: *Am. Mineral.*, XXII, 1052 (1937).

<sup>42</sup> C. S. Hurlbut: *Am. Mineral.*, XXIII, 765 (1938).

<sup>43</sup> E. W. Heinrich: *Am. Mineral.*, XXXI, 71 (1946).

<sup>44</sup> G. B. Boky: *Min. Abst.*, VII, 123 (1938). See also Anna Boldyreva: *Mem. Soc. Russ. Mineral.*, LXVI, 651 (1937). Also *C. R. Acad. Sci. U.R.S.S.*, XXII, 242 (1939).

<sup>45</sup> W. T. Schaller: *U. S. Geol. Surv. Bull.* 610, 41 (1916), and C. Palache: *Am. Mineral.*, XXIII, 644 (1938).



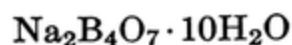
= 0.021. Another sample from Italy is biaxial positive with  $2V = 62^\circ \pm$ , with weak dispersion;  $N_X = 1.470$ ,  $N_Y = 1.488$ ,  $N_Z = 1.542$ ,  $N_Z - N_X = 0.072$ . Color white. Found in Tuscany.

**Tincalconite** ( $Na_2B_4O_7 \cdot 5H_2O$ ) is rhombohedral<sup>46</sup> with  $c/a = 1.850$ . Space group  $R\bar{3}$ ;  $a$  11.3,  $c$  20.9 Å. U.C. 9. Artificial crystals pseudo-octahedral with {0001} and {10 $\bar{1}$ 1}; also {01 $\bar{1}$ 2}.  $G = 1.88$ . Uniaxial positive with  $N_O = 1.461$ ,  $N_E = 1.474$ ,  $N_E - N_O = 0.013$ . Color white. An alteration product of kernite; found in Kern County, California.

**Kernite** ( $Na_2B_4O_7 \cdot 4H_2O$ ) is monoclinic prismatic<sup>46,47</sup> with  $a:b:c = 0.762:1:1.698$ ,  $\beta = 108^\circ 52'$ . Space group  $P2/c$ ;  $a$  6.96,  $b$  9.14,  $c$  15.52 Å. U.C. 4. Crystals nearly equant or elongated parallel to  $c$ . Perfect 001 and 100 and fair  $\bar{1}02$  cleavages. Also 011 parting.  $H = 2.5$ .  $G = 1.925$ . Fuses to white glass after swelling. Very slowly soluble in cold water. The optic plane and  $Z$  are normal to 010;  $X \wedge c = -70.5^\circ$ .  $Z = b$ .  $(- )2V = 80^\circ$ ,  $r > v$ .  $N_X = 1.454$ ,  $N_Y = 1.472$ ,  $N_Z = 1.488$ ,  $N_Z - N_X = 0.034$ . Colorless to white. Found in salt deposits at considerable depth in borings in Kern County, California.

**BORAX**

## MONOCLINIC PRISMATIC



$$a:b:c = 1.114:1:1.159 \quad \beta = 106^\circ 35'$$

**STRUC.** Space group<sup>46</sup>  $C2/c$ ;  $a$  11.82,  $b$  10.61,  $c$  12.30 Å. U.C. 4.

**PHYS. CHAR.** Crystals prismatic, resembling pyroxene; twinning on 100. Perfect 100 and distinct 110 cleavages.  $H = 2$ .  $G = 1.71$ .  $F = 1$ , with swelling, to transparent glass. Soluble in water.

**OPT. PROP.** The optic plane and  $X$  are normal to 010;  $Z \wedge c = +55^\circ 35'$  Na (Tschermak);  $+54^\circ$  (Dufet); strong crossed dispersion. See Fig. 91. By heating from  $21^\circ$  to  $86^\circ C$ . the optic plane is turned  $3^\circ 26'$ . Sections normal to an optic axis show abnormal brown to ultra blue interference colors without extinction.  $(- )2V = 39^\circ 36'$ ,  $r > v$  distinct.  $N_X = 1.447$  Na,  $N_Y = 1.469$ ,  $N_Z = 1.472$ ,  $N_Z - N_X = 0.025$ .  $F - C$  for  $N_Y = 0.0081$ . Color white.

Borax glass has  $G = 2.36$  and  $N = 1.513$  Na.

**OCCUR.** Borax is an important part of certain salt deposits, as in Tibet and California.

**DIAG.** The marked negative relief, moderate birefringence, and strong dispersion are characteristic, especially when combined with the peculiar mode of occurrence.

<sup>46</sup> W. Minder: *Zeit. Krist.*, XCII, 301 (1935).

<sup>47</sup> W. T. Schaller: *Am. Mineral.*, XII, 24 (1927). J. Garrido: *Zeit. Krist.*, LXXXII, 468 (1932). See also J. L. A. Portolés: *Chem. Abst.*, XLII, 1848 (1948).

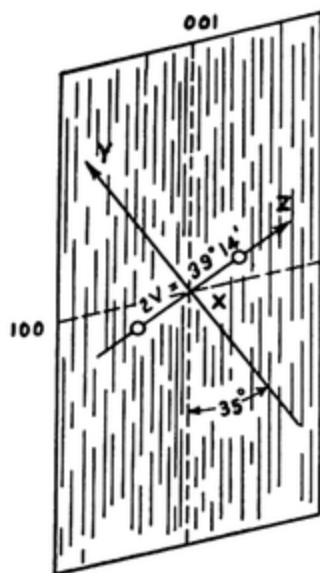


FIG. 91. The optic orientation of borax.

## VIII. SULFATES, ETC.

Sulfates, selenates, tellurates, chromates, molybdates, and tungstates are included in this division, as well as the rare selenites and tellurites, and also polythionates and polychromates. A few salts of two or more oxygen acids (including one acid of this division) are added. The arrangement is based first on the ratio of B to X in the general formula  $A_mB_nX_p$ , and second, on the increasing ratio of A to B. An outline classification follows:

1. Type formula  $A_m(BX_4)_n$  with  $m < n$ .
  - (a) Without additional anions.
  - (b) With additional anions.
2. Type formula  $\approx ABX_4$ .
  - (a) Without additional anions  $\begin{cases} \text{Anhydrous.} \\ \text{Hydrous.} \end{cases}$
  - (b) With additional anions  $\begin{cases} \text{Anhydrous.} \\ \text{Hydrous.} \end{cases}$
3. Type formula  $\approx A_3B_2X_8$ .
  - (a) Without additional anions  $\begin{cases} \text{Anhydrous.} \\ \text{Hydrous.} \end{cases}$
  - (b) With additional anions  $\begin{cases} \text{Anhydrous.} \\ \text{Hydrous.} \end{cases}$
4. Type formula  $\approx A_2BX_4$ .
  - (a) Without additional anions  $\begin{cases} \text{Anhydrous.} \\ \text{Hydrous.} \end{cases}$
  - (b) With additional anions  $\begin{cases} \text{Anhydrous.} \\ \text{Hydrous.} \end{cases}$
5. Type formula  $\approx A_3BX_4$ .
  - (a) With additional anions  $\begin{cases} \text{Anhydrous.} \\ \text{Hydrous.} \end{cases}$
6. Type formula  $A_mBX_4$  with  $m = 4$  or more.
7. Type formula  $A_2B_2X_7$ .
8. Type formula  $A_m(BX_3)_n$ .
9. Sulfates, etc., with salts of other acids  $\begin{cases} \text{Anhydrous.} \\ \text{Hydrous.} \end{cases}$

1. Sulfates with type formula  $A_m(BX_4)_n$  with  $m < n$ 

## (a) WITHOUT ADDITIONAL ANIONS

**Coquimbite**  $[Fe_2(SO_4)_3 \cdot 9H_2O]$  is hexagonal with  $c/a = 1.564$ . Al may proxy for some Fe.  $a$  10.85;  $c$  17.03 Å. Crystals short prismatic or rhombohedral. Twinning on 0001. Poor 10 $\bar{1}0$ , 10 $\bar{1}1$ , and 01 $\bar{1}1$  cleavages.  $H. = 2$ .  $G. = 2.1$ .  $F. = 4.5-5$ . Soluble in cold water. Uniaxial positive with  $N_O = 1.5469$  Li, 1.5519 Na,  $N_E = 1.5508$  Li, 1.5575 Na,  $N_E - N_O = 0.0039$  Li, 0.0056 Na; the strong dispersion produces abnormal interference colors. Color white, yellow, brown, violet. Found at mines in Chile and Arizona; also known at Vesuvius. Very rare. Another phase, known as *paracoquimbite*,<sup>1</sup> has been recognized in Chile. It is rhombohedral, with  $c/a = 4.693$ .  $G. = 2.11$ .

**Ferrimolybdenite**<sup>2</sup>  $[Fe_2(MoO_4)_3 \cdot 8H_2O?]$  is orthorhombic with  $a:b:c = 0.387:1:0.475$ . Crystals fibrous parallel to  $c$ , with distinct 001 cleavage.  $H. = 1-2$ .  $G. = 4.5$ .  $F. =$  easy. Soluble in acids and decomposed by  $NH_4OH$ . The optic plane is 100;  $Z = c$ .  $(+ )2V = 28^\circ \pm$ ,  $r < v$  marked.  $N_X = 1.72-1.78$ ,  $N_Y = 1.733-1.79$ ,  $N_Z = 1.87-2.05$  (Larsen<sup>3</sup>). Color sulfur yellow, with X and Y = clear, Z = dirty gray to canary yellow; thick fibers nearly opaque parallel to Z (= elongation). Apparently an alteration product of molybdenite. Found at Mulgine, West Australia.

**Ransomite**<sup>4</sup>  $[CuFe''(SO_4)_4 \cdot 7H_2O]$  is orthorhombic with  $a:b:c = 0.574:1:0.297$ . Crystals slender prismatic and complex. Perfect pinacoidal or prismatic cleavage.  $H. = 2.5$ .  $G. = 2.63$ .  $(+ )2V =$  small.  $N_X = 1.631$ ,  $N_Y = 1.643$ ,  $N_Z = 1.695$ ,  $N_Z - N_X = 0.064$ . Color blue. Produced by a fire in the United Verde mine, Arizona.

**Lausenite**<sup>5</sup>  $[Fe_2(SO_4)_3 \cdot 6H_2O]$  (originally called rogersite<sup>4</sup>) is monoclinic and vertically elongated. No observed cleavage. The optic plane is 010 (artificial crystals).  $X \wedge c = 27^\circ$ .  $(- )2V =$  large.  $N_X = 1.598$ ,  $N_Y = 1.628$ ,  $N_Z = 1.654$ ,  $N_Z - N_X = 0.056$ . Colorless. Produced by a fire in the United Verde mine, Arizona.

**Alunogen**<sup>6</sup>  $[Al_2(SO_4)_3 \cdot 16?H_2O]$  is triclinic pinacoidal<sup>7</sup> with  $a:b:c = 0.836:1:0.675$ ,  $\alpha = 89^\circ 58'$ ,  $\beta = 97^\circ 26'$ ,  $\gamma = 91^\circ 52'$ . Crystals {010} scales or fibers parallel to  $c$ . Perfect 010 cleavage.  $H. = 1.5-2$ .  $G. = 1.65; 1.785$  (Lausen<sup>4</sup>).  $F. = 7$ . Soluble in water. The optic plane is normal to 010 cleavage trace;  $Z \wedge c = 42^\circ$ .  $(+ )2V = 69^\circ$ ,  $N_X = 1.475$ ,  $N_Y = 1.478$ ,  $N_Z = 1.485$ ,  $N_Z - N_X = 0.010$ .  $(+ )2V =$  small  $N_X = 1.473$ ,  $N_Y = 1.474$ ,  $N_Z = 1.480$ ,  $N_Z - N_X = 0.007$  (Larsen<sup>3</sup>)

<sup>1</sup> H. Ungemach: *Bull. Soc. Fr. Min.*, LVIII, 165 (1935); M. C. Bandy: *Am. Mineral.*, XXIII, 669 (1938). R. Rost (*Min. Abst.*, IX, 204, 1946) argues that *paracoquimbite* is a synonym of *slavikite* and both have the composition  $Fe_2(OH)(SO_4)_2 \cdot 4H_2O$ .

<sup>2</sup> E. S. Simpson: *Min. Abst.*, III, 131 (1926), gives the formula:  $Fe_2O_3 \cdot 4MoO_3 \cdot 5H_2O + 5H_2O$ .

<sup>3</sup> E. S. Larsen: *U. S. Geol. Surv. Bull.* 679 (1921) and 848 (1934).

<sup>4</sup> C. Lausen: *Am. Mineral.*, XIII, 203 (1928);  $a$  and  $b$  interchanged to make  $a < b$ .

<sup>5</sup> G. M. Butler: *Am. Mineral.*, XIII, 594 (1928).

<sup>6</sup> Study of dehydration by E. S. Larsen and G. Steiger: *Am. Jour. Sci.*, CCXV, 1 (1928).

<sup>7</sup> S. G. Gordon: *Not. Nat. Acad. Sci. Phila.*, CI (1942).

(Uhlig<sup>9</sup>). Color white. Found about volcanoes and also in alum shales, as in Bolivia and Utah.

**Meta-alunogen**<sup>9</sup>  $[\text{Al}_2(\text{SO}_4)_3 \cdot 13.5\text{H}_2\text{O}]$  is monoclinic. X normal to cleavage. (+)2V = moderate,  $N_Z = 1.491$ ,  $N_Y = 1.473$ ,  $N_X = 1.469$ ,  $N_Z - N_X = 0.022$ . White, waxy, or pearly. Produced by partial dehydration of alunogen. Rare.

<b>HALOTRICHITE</b>	MONOCLINIC PRISMATIC <sup>9</sup>	$\text{FeAl}_2(\text{SO}_4)_4 \cdot 22\text{H}_2\text{O}$
<b>PICKERINGITE</b> <sup>10</sup>	MONOCLINIC PRISMATIC	$\text{MgAl}_2(\text{SO}_4)_4 \cdot 22\text{H}_2\text{O}$
<b>APJOHNITE</b>	MONOCLINIC PRISMATIC	$\text{MnAl}_2(\text{SO}_4)_4 \cdot 22\text{H}_2\text{O}$
<b>DIETRICHITE</b>	MONOCLINIC PRISMATIC	$(\text{Zn, Fe, Mn})\text{Al}_2(\text{SO}_4)_4 \cdot 22\text{H}_2\text{O}$
<b>BILINITE</b>	MONOCLINIC PRISMATIC	$\text{FeFe}_2(\text{SO}_4)_4 \cdot 22\text{H}_2\text{O}$

COMP. These end-members probably all belong to one continuous system, but continuity is not established.

STRUC. Space group<sup>10</sup>  $P2/m$ . For halotrichite  $a$  20.5,  $b$  24.2,  $c$  6.17 Å. U.C. 4.  $a:b:c = 0.845:1:0.254$ ,  $\beta = 100^\circ 40'$ . For pickeringite  $a$  20.8,  $b$  24.2,  $c$  6.17 Å. U.C. 4.  $a:b:c = 0.866:1:0.255$ ,  $\beta = 96^\circ 34'$ .

PHYS. CHAR. Crystals acicular to fibrous. H. = 1–1.5. Poor 010 cleavage. Soluble in water; astringent taste.

OPT. PROP. The optic plane is 010 (except in dietrichite).

	$Z \wedge c$	(-)2V	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$	G.	Color
Halotrichite <sup>11</sup>	+38°	35°	1.480	1.486	1.490	0.010	1.895	White, yellow, pale green
Pickeringite	+36°	60°	1.475	1.480	1.483	0.008	1.83	White
Apjohnite	+29°	Small	1.478	1.482	1.482	0.004	1.8 ±	White
Dietrichite	+29°(+)	Large	1.475	1.480	1.488	0.013		White
Bilinite	+39°			1.500		Weak	1.87	White; yellow

Colorless, white, or stained gray, yellow, or red.

OCCUR. Produced by the action of sulfuric acid solutions on rocks and ores, as at Bodenmais, Bavaria; Newport, Nova Scotia; Alum Creek, New Mexico; etc.

**Quenstedtite**<sup>12</sup>  $[\text{Fe}_2(\text{SO}_4)_3 \cdot 10\text{H}_2\text{O}]$  is triclinic pinacoidal with  $a:b:c = 0.262:1:0.278$ ,  $\alpha = 94^\circ 10'$ ,  $\beta = 101^\circ 44.5'$ ,  $\gamma = 96^\circ 18.5'$ . Multiple twinning as in plagioclase. Crystals {010} tablets<sup>10</sup> with good 100 cleavage. X is at  $\phi = -43^\circ$ ,  $\rho = 45^\circ$ ; Y is at  $\phi = 128^\circ$ ,  $\rho = 43^\circ$ ; Z is at  $\phi = -138^\circ$ ,  $\rho = 88^\circ$ . Extinction on 010 is at  $30^\circ$  to 001. (+)2V =  $70^\circ$ ,  $r < v$ , strong, with horizontal dispersion.  $N_X = 1.547$ ,  $N_Y = 1.566$ ,  $N_Z = 1.594$ ,  $N_Z - N_X = 0.047$ . Colorless, lilac, or violet. Found at times with copiapite. Alters to coquimbite.

<sup>8</sup> J. Uhlig: *Cent. Mineral.*, 1912, 723 and 766.

<sup>9</sup> S. G. Gordon: *Not. Nat. Acad. Sci. Phila.*, CI (1942). *Min. Abst.*, VIII, 278 (1942). Gordon found pickeringite to be monoclinic spenoidal.

<sup>10</sup> M. C. Bandy: *Am. Mineral.*, XXIII, 669 (1938).

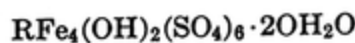
<sup>11</sup> With 21 H<sub>2</sub>O halotrichite has G. = 1.87,  $Z \wedge c = 31^\circ\text{--}33^\circ$ ,  $N_X = 1.478$ ,  $N_Y = 1.481$ ,  $N_Z = 1.484$ ,  $N_Z - N_X = 0.006$ . See V. Lo Sardo: *Per. Min. Roma*, VIII, 281 (1937); *Min. Abst.*, VII, 216 (1939).

<sup>12</sup> H. Ungemach: *Comp. Rend. Acad. Sci. Paris*, CXCVII, 1132 (1933).

**Roemerite**  $[Fe''Fe'''_2(SO_4)_4 \cdot 14H_2O]$  is triclinic pinacoidal<sup>13</sup> with  $a:b:c = 0.421:1:0.417$ ,  $\alpha = 91^\circ 17'$ ,  $\beta = 100^\circ 30'$ ,  $\gamma = 85^\circ 31'$ . Crystals {010} plates; granular. Perfect 010 and distinct 001 cleavages.  $H. = 3-3.5$ .  $G. = 2.15 \pm$ .  $F. = 4.5-5$ . Soluble in water.  $(- )2V = 51^\circ$ ,  $r > v$  very strong, with strong crossed dispersion—sections normal to Y and Z give sharp extinction, but sections normal to X give no extinction and very abnormal interference colors.  $N_X = 1.524$ ,  $N_Y = 1.571$ ,  $N_Z = 1.583$ ,  $N_Z - N_X = 0.059$  (Landon<sup>14</sup>);  $N_X = 1.526$ ,  $N_Y = 1.564$ ,  $N_Z = 1.575$ ,  $N_Z - N_X = 0.049$  (Bandy<sup>10</sup>). Color brown, with  $Y > X = Z$  in brown tints. Found in ore deposits in northern Chile. Among soluble sulfates roemerite resembles only quetenite and the latter is monoclinic.

**COPIAPITE**<sup>10,15,16</sup>

## TRICLINIC PINACOIDAL



$$a:b:c = 0.401:1:0.397 \quad \alpha = 93^\circ 58' \quad \beta = 102^\circ 8' \quad \gamma = 98^\circ 50'.$$

**COMP.** Tenor of water seems to vary from 14 to 21  $H_2O$ ; R may be Fe, Mg, Al, or Cu (or even O?).

**STRUC.** Space group  $P\bar{1}$ .  $a$  7.33,  $b$  18.15,  $c$  7.27 Å. U.C. 1.

**PHYS. CHAR.** Crystals {010} plates, or fibrous, with perfect 010 cleavage.  $H. = 2.5$ .  $G. = 2.1-2.2$ .  $F. = 4.5-5$ . Soluble in water.

**OPT. PROP.** The optic plane is (nearly) normal to 010;  $X \wedge c = +58^\circ$  (Lacroix<sup>17</sup>);  $Z \wedge c = -53^\circ$  (McCaughey<sup>18</sup>);  $Z \wedge c = 50^\circ$  (Walker<sup>19</sup>).  $(+)2V = 45^\circ-74^\circ$ ,  $r > v$ .  $N_X = 1.506-1.540$ ,  $N_Y = 1.528-1.550$ ,  $N_Z = 1.575-1.600$ ,  $N_Z - N_X = 0.057-0.070$ .  $F - C$  for  $N_Y = 0.018$ . Variations doubtless correspond with variations in composition. For example, a sample with 5.7 CuO has  $N_Y = 1.591$  and  $N_Z = 1.620$ . Color yellow, reddish, violet, with  $X =$  yellowish green,  $Y =$  very pale yellowish,  $Z =$  sulfur yellow. So-called sulfur in coal may be copiapite.

**OCCUR.** Copiapite is usually an alteration product of iron sulfide or melanterite. Not very rare.

## (b) WITH ADDITIONAL ANIONS

**Louderbackite**<sup>4</sup>  $[Fe''_2Fe'''_6(OH)_2(SO_4)_{10} \cdot 34H_2O?]$  is orthorhombic in crusts. Two good cleavages apparently pinacoidal.  $H. = 2.5-3$ .  $G. = 2.19$ . Soluble in water.  $(+)2V = 75^\circ$  calc.,  $N_X = 1.544$ ,  $N_Y = 1.558$ ,  $N_Z = 1.581$ ,  $N_Z - N_X = 0.037$ . Produced by a fire in the United Verde mine, Arizona.

<sup>13</sup> C. W. Wolfe: *Am. Mineral.*, XXII, 736 (1937).

<sup>14</sup> R. E. Landon: *Am. Mineral.*, XII, 279 (1927).

<sup>15</sup> C. Palache, M. A. Peacock, and L. G. Berry: *Univ. Toronto Geol. Ser.*, 50, 9 (1946). See also R. Rost: *Min. Abst.*, IX, 204 (1946), who reports  $X = b$ ,  $Y \wedge c = 38.5^\circ$ , monoclinic.

<sup>16</sup> H. Ungemach: *Bull. Soc. Fr. Min.*, LVIII, 97 (1935); also L. G. Berry: *Univ. Toronto Geol. Ser.*, 41, 7 (1938), *Min. Abst.*, VII, 365 (1939).

<sup>17</sup> A. Lacroix: *Minéral. France*, IV, 248 (1910). Optic orientation given differently because of varying crystal orientation.

<sup>18</sup> W. J. McCaughey: *Am. Mineral.*, III, 162 (1918).

<sup>19</sup> T. L. Walker: *Univ. Toronto Geol. Ser.*, 14, 84 (1922).

2. Sulfates with type formula  $\approx ABX_4$ 

## (a) WITHOUT ADDITIONAL ANIONS—ANHYDROUS

**SCHEELITE**      TETRAGONAL DIPYRAMIDAL       $c/a = 1.530$        $\text{CaWO}_4$

STRUC.<sup>20</sup> Space group  $I4_1/a$ ;  $a$  7.44,  $c$  11.35; U.C. 8.

COMP. Molybdenum may proxy for considerable tungsten.

PHYS. CHAR. Crystals pyramidal, or thick basal tablets; often massive. Twinning on 100 or 110. Distinct 111 cleavage.  $H. = 4.5-5$ .  $G. = 6.12$  (5.94 with 8%  $\text{MoO}_3$ ).  $F. = 5$ . Decomposed by  $\text{HCl}$ , leaving a yellow residue. Gives a deep blue color when powder is boiled with  $\text{HCl}$  and again boiled after zinc or tin is added.

OPT. PROP. Uniaxial positive with  $N_O = 1.9185$  (red),  $N_E = 1.9345$ ,  $N_E - N_O = 0.016$ . Again<sup>21</sup> for  $\lambda = 671.6$  (Li),  $N_O = 1.9109$ ,  $N_E = 1.9265$ ,  $N_E - N_O = 0.0156$ ; for  $\lambda = 589$  (Na)  $N_O = 1.9204$ ,  $N_E = 1.9368$ ,  $N_E - N_O = 0.0164$ ; and for  $\lambda = 491.6$   $N_O = 1.9377$ ,  $N_E = 1.9554$ ,  $N_E - N_O = 0.0177$ . Color white, yellow, brownish, gray.

ALTER. Alteration to wolframite is common.

OCCUR. Scheelite is found in veins with quartz and gold ores; in pegmatites with cassiterite, topaz, fluorite, molybdenite, wolframite; in crystalline rocks.

DIAG. It differs from stolzite and wulfenite in optic sign and in much weaker birefringence.

**Powellite** ( $\text{CaMoO}_4$ ) is tetragonal dipyramidal with  $c/a = 1.551$ . Space group<sup>21</sup>  $I4_1/a$ ;  $a$  7.40,  $c$  11.44 Å. U.C. 8. Crystals pyramidal; distinct 111 cleavage.  $H. = 3.5$ .  $G. = 4.35$  (4.5 with some  $\text{WO}_3$ ).  $F. = 4$ . Decomposed by  $\text{HCl}$ . Uniaxial positive with  $N_O = 1.967$ ,  $N_E = 1.978$ ,  $N_E - N_O = 0.011$  (with 10%  $\text{WO}_3$ ). Color greenish yellow. Found in ore deposits, as in western Idaho.

**Wulfenite** ( $\text{PbMoO}_4$ ) is tetragonal dipyramidal<sup>20</sup> with  $c/a = 1.577$ . Space group  $I4_1/a$ ;  $a$  7.65,  $c$  12.08 Å. U.C. 8. Crystals basal tablets or prismatic or pyramidal. Distinct 111 cleavage.  $H. = 2.5-3$ .  $G. = 6.9$ .  $F. = 2$ . Decomposed by  $\text{HCl}$ . Uniaxial negative with  $N_O = 2.402$  Li,  $N_E = 2.304$ ,  $N_O - N_E = 0.098$ . Again:<sup>22</sup>  $N_O = 2.38$ ,  $N_E = 2.30$ ,  $N_O - N_E = 0.08$ . Also may be distinctly biaxial. Color yellow, red, green, white. Colored crystals pleochroic with  $X < Z$ . Found in the oxide zone of veins with lead ores, as in Austria, Baden, and Arizona.

**Stolzite** ( $\text{PbWO}_4$ ) is tetragonal dipyramidal<sup>20</sup> with  $c/a = 1.561$ .  $a$  7.97,  $c$  12.01 Å. Crystals pyramidal with poor 001 cleavage.  $H. = 3$ .  $G. = 8.2-8.34$ .  $F. = 2$ . Decomposed by  $\text{HNO}_3$ . Uniaxial negative with  $N_O = 2.2685$ ,  $N_E = 2.182$ ,  $N_O - N_E = 0.0865$ . Color green, gray, brown, red. Streak colorless. Found in veins, as in Bohemia and Chile.

**Bellite** ( $\text{PbCrO}_4$ , with  $\text{As}_2\text{O}_3$ ?) is hexagonal in velvety coatings; acicular.  $H. = 2.5$ .  $G. = 5.5$ .  $F. = \text{easy}$ . Uniaxial negative with  $N_O = 2.16$ ,  $N_E = 2.14$ ,  $N_O - N_E = 0.02$ . Color crimson, yellow, orange; weakly pleochroic with  $X < Z$ . Found in an ore deposit at Magnet, Tasmania. Probably a mixture.

<sup>20</sup> L. Vegard: *Phil. Mag.*, I, 1151 (1926), and *Skr. Norske Vidensk. Oslo*, No. 2 (1927).

<sup>21</sup> Z. Harada: *Jour. Sci. Hokkaido Imp. Univ.*, IV, II, 4, 279 (1934).

<sup>22</sup> O. W. Jarrell: *Am. Mineral.*, XXIV, 629 (1939). F. Rinne, H. Hentschel, and E. Schiebold: *Zeit. Kryst.*, LXI, 164 (1925).



## ANHYDRITE

## ORTHORHOMBIC DIPYRAMIDAL



$$a:b:c = 0.893:1:1.001$$

STRUC. Space group  $Bbmm$ ;  $a$  6.24,  $b$  6.98,  $c$  6.98 Å. U.C. 4.

PHYS. CHAR. Crystals uncommon, varied. Twinning on 012, or lamellar on 101. Perfect 001 and 010 and distinct 100 cleavages.  $H. = 3$ .  $G. = 2.93$ . Fusible at  $1450^\circ \text{C}$ . after inversion at  $1193^\circ \text{C}$ . Soluble in  $\text{HCl}$ .

OPT. PROP. The optic plane is 010;  $Z = a$ . See Fig. 92. The optic angle decreases slowly with heat.  $(+)2V = 42^\circ$ ,  $r < v$  distinct.

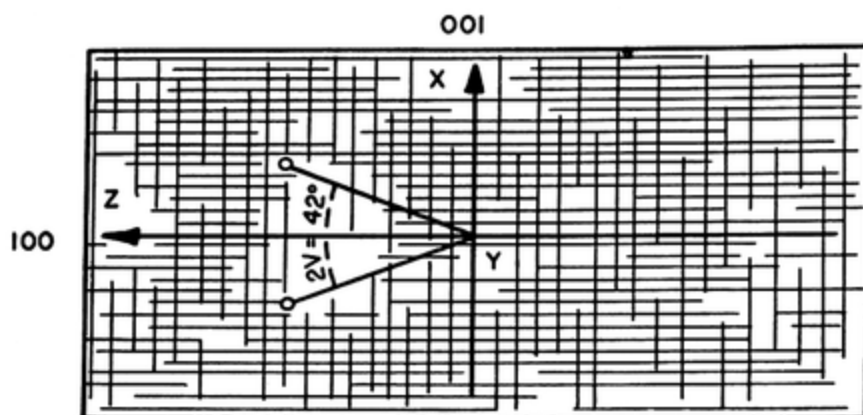


FIG. 92. The optic orientation of anhydrite.

$N_X = 1.570$ ,  $N_Y = 1.576$ ,  $N_Z = 1.614$ ,  $N_Z - N_X = 0.044$ .  $F - C$  for  $N_Y = 0.0078$ . Again:<sup>23</sup>  $(+)2V = 36^\circ$ ,  $N_X = 1.573$ ,  $N_Y = 1.579$ ,  $N_Z = 1.618$ ,  $N_Z - N_X = 0.045$ .

Color white, grayish, bluish, red. Rare violet varieties are pleochroic with  $X$  and  $Z$  violet,  $Y$  colorless.

INVER. Anhydrite inverts<sup>24</sup> at  $1195^\circ \text{C}$ . to  $\alpha\text{-CaSO}_4$ , which is monoclinic with lamellar twinning like plagioclase. Anhydrite ( $\beta\text{-CaSO}_4$ ) and  $\gamma\text{-CaSO}_4$  are monotropic;  $\gamma\text{-CaSO}_4$  (sometimes called "soluble anhydrite") has<sup>25</sup>  $N_X = 1.544$ ,  $N_Z = 1.555$ . It is easily produced by dehydration of gypsum at about  $200^\circ \text{C}$ .

ALTER. Anhydrite may hydrate slowly to gypsum.

OCCUR. It is usually associated with gypsum and halite.

DIAG. The rectangular cleavages in three directions and the strong birefringence are characteristic.

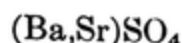
<sup>23</sup> C. O. Hutton: *Trans. Roy. Soc. N. Zeal.*, LXXIV, 125 (1944).

<sup>24</sup> W. Grahmann: *Zeit. anorg. Chem.*, LXXXI, 257 (1913). For details of changes with slow heating see D. S. Belyankin and V. V. Lapin: *Min. Abst.*, X, 109 (1947).

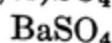
<sup>25</sup> D. S. Belyankin and K. M. Feodotiev: *Min. Abst.*, VII, 280 (1939).

**BARYTOCELESTITE**

ORTHORHOMBIC DIPYRAMIDAL

**Barite**

$a:b:c = 0.815:1:1.314$

**Celestite**

$a:b:c = 0.779:1:1.280$



COMP. Nearly pure end-members are usually found in nature, but the series is probably continuous and intermediate types are known. See Fig. 93. A little  $\text{CaSO}_4$  or up to 30%  $\text{PbSO}_4$  may be present.

STRUC. Space group *Pnma*; for barite:<sup>26</sup>  $a$  8.85,  $b$  5.43,  $c$  7.13 Å whence  $a/2:b:c = 0.815:1:1.314$ ; for celestite:  $a$  8.36,  $b$  5.36,  $c$  6.84 Å whence  $a/2:b:c = 0.780:1:1.276$ ; U.C. 4.

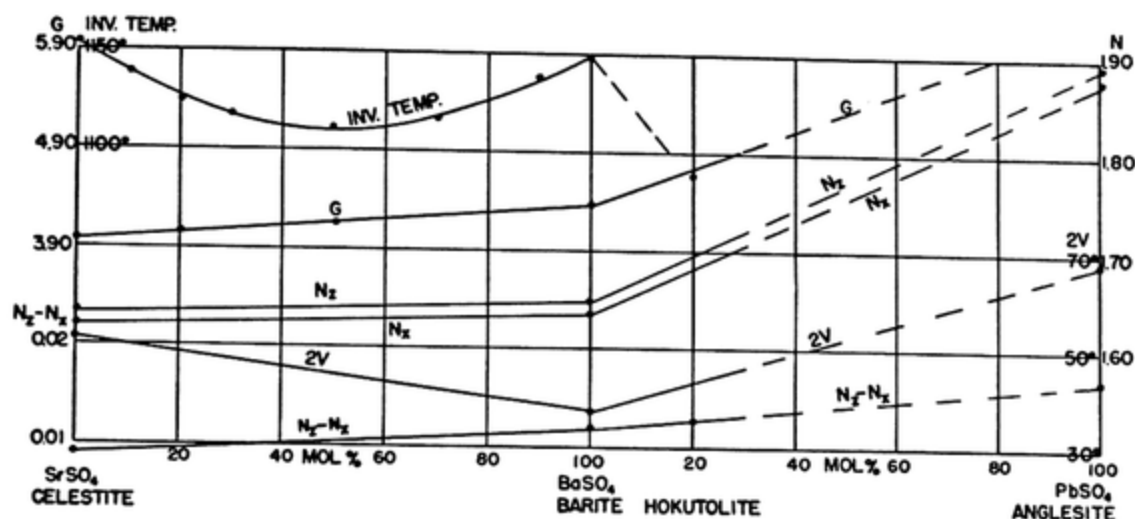


FIG. 93. Properties of barytocelestite (and anglesite).

PHYS. CHAR. Crystals thick basal tablets, or elongated parallel to  $a$  or  $b$ , with perfect 001 and 110 and poor 010 cleavages with a prismatic cleavage angle of  $78^\circ 22'$  (barite) to  $75^\circ 50'$  (celestite).  $H. = 3$  (barite) to 3.5 (celestite).  $G. = 4.5$  (barite) to 4.00 (celestite). Fuses at  $1580^\circ \text{C.}$  after inversion at  $1149^\circ \text{C.}$  (barite); and at  $1605^\circ \text{C.}$  after inversion at  $1152^\circ \text{C.}$  (celestite). Insoluble.

OPT. PROP.<sup>27</sup> The optic plane is 010;  $Z = a$ . See Fig. 94.

	(+)2V	$r < v$	$N_x$	$N_y$	$N_z$	$N_z - N_x$	$N_z' - N_x$ <sup>28</sup> on 110	F-C( $N_y$ )
$\text{BaSO}_4$	$37^\circ 30'$	Weak	1.636	1.637	1.648	0.012	0.006	0.009
$\text{SrSO}_4$	$50^\circ 0'$	Distinct	1.622	1.623	1.631	0.009	0.0044	0.0084

The optic angle increases with rise of temperature: for  $\text{BaSO}_4$ ,  $2E = 62^\circ 40'$  at  $20^\circ \text{C.}$  and  $93^\circ 53'$  Na at  $300^\circ \text{C.}$ ; for  $\text{SrSO}_4$ ,  $2E = 70^\circ 20'$  at  $-190^\circ \text{C.}$ ,  $87^\circ 28'$  at  $15^\circ \text{C.}$  and  $130^\circ 26'$  Na at  $300^\circ \text{C.}$

<sup>26</sup> R. W. James and W. A. Wood: *Proc. Roy. Soc. London*, A, CIX, 598 (1925).

<sup>27</sup> Very full data given by R. Kolb: *Zeit. Krist.*, XLIX, 24 (1911).

<sup>28</sup> H. Buttgenbach: *Minéraux et Roches*, 1916, 510.

Barite with 30%  $PbSO_4$  has been found in Japan; it has indices between 1.650 and 1.700 with  $N_Z - N_X = 0.012$  to 0.014.

Color white, yellowish, gray, blue, red, brown. Celestite is named from its common sky-blue color. Deeply colored types are pleochroic at least in thick sections.

**OCCUR.** Barite is abundant in some metalliferous veins; it is found in limestones and sandstones, and in amygdules in some basaltic rocks.

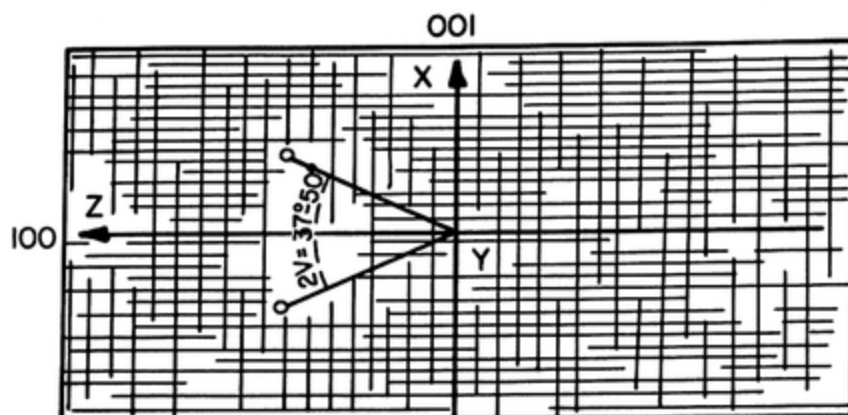


FIG. 94. The optic orientation of barytocelestite.

Celestite is usually associated with limestone or sandstone; it is also found in veins and in beds of gypsum, halite, etc.

**DIAG.** Barite and celestite have lower relief and weaker birefringence than anglesite; anhydrite has three easy rectangular cleavages and very strong birefringence.

#### ANGLESITE

#### ORTHORHOMBIC DIPYRAMIDAL

#### $PbSO_4$

$$a:b:c = 0.785:1:1.289$$

**STRUC.** Space group <sup>29</sup>  $Pnma$ ;  $a$  8.45,  $b$  5.38,  $c$  6.93 Å whence  $a/2:b:c = 0.795:1:1.288$ . U.C. 4.

**PHYS. CHAR.** Crystals varied, with distinct 001 and 110 cleavages and a prismatic cleavage angle of  $76^\circ 16'$ .  $H. = 3$ .  $G. = 6.3$ . Fuses at  $1080^\circ C$ . after inversion at  $852^\circ C$ . Slowly soluble in  $HNO_3$ .

**OPT. PROP.**<sup>27</sup> The optic plane is 010;  $Z = a$ . See Fig. 95.  $(+2V) = 60^\circ - 75^\circ$ ,  $r < v$  strong.  $N_X = 1.878$ ,  $N_Y = 1.883$ ,  $N_Z = 1.895$ ,  $N_Z - N_X = 0.017$ ;  $F-C$  for  $N_Y = 0.026$ . The optic angle increases with rise of temperature;  $2E = 62^\circ 22'$  Na at  $20^\circ C$ . and  $92^\circ 40'$  at  $200^\circ C$ .

Color white, yellowish, grayish, etc. Colorless in thin section.

**OCCUR.** Anglesite is usually associated with galena, of which it is often an oxidation product; sometimes also with cerussite in veins and ore bodies.

**DIAG.** It is characterized by very high relief, moderate birefringence, and large optic angle. Cerussite has extreme birefringence.

<sup>29</sup> E. K. Broch: *Skr. Oslo*, I, No. 8 (1929).

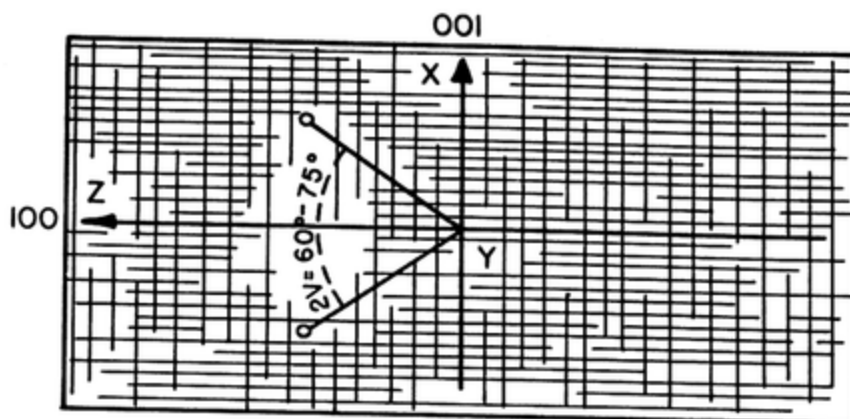


FIG. 95. The optic orientation of anglesite.

**WOLFRAMITE**MONOCLINIC PRISMATIC<sup>29</sup>(Fe,Mn)WO<sub>4</sub>

$$a:b:c = 0.825:1:0.866 \quad \beta = 90^\circ 28'$$

COMP. Wolframite forms a complete series from ferberite (FeWO<sub>4</sub>) to hübnerite (MnWO<sub>4</sub>).

STRUC. Space group<sup>29</sup> *P2/c*; U.C. 2. For FeWO<sub>4</sub>: *a* 4.70, *b* 5.69, *c* 4.93 Å,  $\beta = 90^\circ$ ; for MnWO<sub>4</sub>: *a* 4.84, *b* 5.76, *c* 4.97 Å,  $\beta = 90^\circ 53'$ .

PHYS. CHAR. Crystals long prismatic; also {100} tablets, bladed, or lamellar; granular, massive. Perfect 010 cleavage; 100 and 102 parting. H. = 5–5.5. G. = 7.18 (MnWO<sub>4</sub>) to 7.61 (FeWO<sub>4</sub>). F. = 2 (FeWO<sub>4</sub>) to 4 (MnWO<sub>4</sub>). Decomposed by acid.

OPT. PROP. The optic plane and X are normal to 010;  $Z \wedge c = -17^\circ$  to  $-27^\circ$  or more, apparently larger in ferberite.<sup>30</sup> See Fig. 96. Optic angle large,  $60^\circ$ – $70^\circ$ ; optically positive.

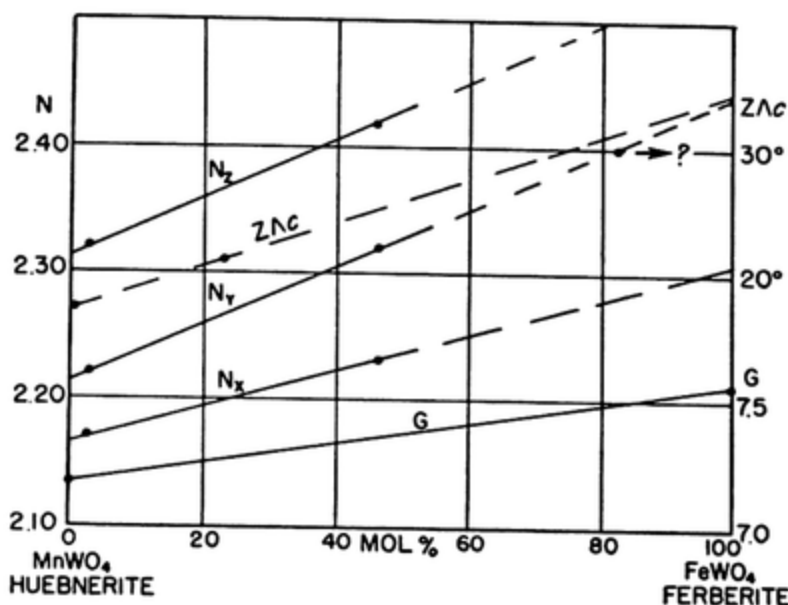


FIG. 96. Properties of wolframite.

<sup>30</sup> L. Capdecombe (*Bull. Soc. Fr. Min.*, LXIV, 171, 1941) found  $Z \wedge c = 27^\circ$  in opaque (unanalyzed) wolframite. See R. Bailly: *Am. Mineral.*, XXXIII, 519 (1948), for infrared data.

	Wolframite					Hübnerite			
Ferberite	18.3 <sup>31</sup>	?	?	5.87 <sup>32</sup>	11.9 <sup>31</sup>	0.55 <sup>31</sup>	?	?	0.0 <sup>31</sup>
FeO = 23.7 <sup>31</sup>	4.6	?	?	19.26	11.7	23.31	?	?	23.4
MnO = 0.0						73°	75° <sup>33</sup>	Large <sup>3</sup>	
(+) $2V = 68^\circ$			Large <sup>33</sup>	Large					
$N_X = 2.255$	2.269	2.31	2.26		2.200	2.17		2.20	2.150
$N_Y = 2.305$	2.328		2.32		2.263	2.22			2.195
$N_Z = 2.414$	2.444	2.46 <sup>33</sup>	2.42 Li		2.360	2.32		2.30	2.283
$N_Z - N_X = 0.159$	0.175	0.15	0.16		0.160	0.15		0.10	0.133
$Z \wedge c =$				21°		19°	17°		

Color brownish red (or brown) to black. Streak brown, gray, black. In thin section ferberite is opaque, but the clearest central part of crystals of hübnerite may be green; pleochroic (with exceptions)  $X < Y < Z$  (or <sup>32</sup>  $X > Y > Z$ ), as follows:

Wolframite from Portugal <sup>32</sup>	Hübnerite from Butte, Montana, 0.1 mm. thick	Hübnerite from France
X = Deep red-brown	Yellowish green to yellowish brown and blood red	Golden yellow
Y = Red-brown	Pale green grading into brown	Yellowish brown
Z = Paler red-brown	Grass green to dark brown and blood red	Greenish yellow

Reflection percentages for wolframite<sup>34</sup> for red 14, for orange 15, for green 17.

OCCUR. Wolframite is found in veins with copper, manganese, tin ores; often associated with scheelite, fluorite, hematite, rhodochrosite.

DIAG. It differs from sphalerite in being anisotropic and from rutile in having inclined extinction.

**Raspite** ( $\text{PbWO}_4$ ) is monoclinic with  $a:b:c = 1.345:1:1.114$ ,  $\beta = 107^\circ 37'$ . Crystals 100 tablets, twinned on 100. Perfect 100 cleavage.  $H. = 2.5$ .  $F. = 2.5-3$ . Decomposed by HCl. The optic plane is 010;  $X \wedge c = \text{large}$ .  $(+ )2V = \text{very small}$ ,  $N_X = 2.27$ ,  $N_Y = 2.27$ ,  $N_Z = 2.30$ ,  $N_Z - N_X = 0.03$ . Color brownish yellow with maximum absorption parallel to Z. Found with stolzite at the Broken Hill mines, Australia.

## CROCOITE

### MONOCLINIC PRISMATIC



$$a:b:c = 0.960:1:0.916 \quad \beta = 102^\circ 27'$$

STRUC.<sup>35</sup> Space group  $P2_1/c$ ;  $a$  7.108,  $b$  7.410,  $c$  6.771 Å. U.C. 4.

PHYS. CHAR. Crystals prismatic, etc.; prism faces vertically striated. Distinct 110 cleavage at an angle of  $86^\circ 19'$ .  $H. = 2.5-3$ .  $G. = 6.0$ .  $F. = 1.5$ .

OPT. PROP. The optic plane is 010;  $Z \wedge c = -5.5^\circ$ .  $(+ )2V = 57^\circ \text{ ca.}$ ,  $r > v$  weak with marked inclined dispersion.  $N_X = 2.31$  Li,  $N_Y = 2.37$ ,  $N_Z = 2.66$ ,

<sup>31</sup> R. Bailly: *Ann. Soc. Geol. Belg.*, LXV, B133 (1942); *Min. Abst.*, X, 161 (1947); *Am. Mineral.*, XXXIII, 519 (1948).

<sup>32</sup> L. Duparc: *Min. Abst.*, III, 138 (1926).

<sup>33</sup> F. S. Dana: *System Mineral.*, 6th Ed., 983 (1892).

<sup>34</sup> H. Schneiderhöhn and P. Ramdohr: *Lehrb. Erzmetall.*, II, 606 (1931).

<sup>35</sup> S. Gliszczynski: *Zeit. Krist.*, CI, 1 (1939).

$N_z - N_x = 0.35$ . Color hyacinth red. Streak orange yellow. Luster adamantine to vitreous.

**OCCUR.** Crocoite is found in the oxide zone in veins with pyrite, gold, galena, vanadinite, etc., as in Maricopa County, Arizona.

**DIAG.** The color, extreme birefringence, and extinction angle are characteristic.

### (a) WITHOUT ADDITIONAL ANIONS—HYDROUS

ALUM	Potassalumite or potassium alum	$KAl(SO_4)_2 \cdot 12H_2O$
	Tschermigite or ammonium alum	$NH_4Al(SO_4)_2 \cdot 12H_2O$

**COMP.** A continuous series is known<sup>36</sup> with properties showing almost exactly rectilinear variation. Many other alums have been made,<sup>37</sup> such as  $KCr$ ,  $NH_4Cr$ ,  $RbCr$ , etc.

**STRUC.** Space group<sup>38</sup>  $Pa3$ ; for K-alum  $a$  12.133; for  $NH_4$ -alum  $a$  12.215 Å. U.C. 4.

**PHYS. CHAR.** Crystals isometric diploidal, usually octahedral or cubic in habit. No cleavage. Often fibrous. Twinning on 111.  $H. = 2$ .  $G. = 1.757$  (K-alum), 1.64 ( $NH_4$ -alum).  $F. = 1$ . Soluble in water.

**OPT. PROP.** Isotropic with marked negative relief.  $N = 1.453$ – $1.458$  (K-alum), 1.457 ( $NH_4$ -alum). May be weakly anisotropic. Colorless.

**INVER.** Potassalumite changes easily to another phase known as *kalinite*, which is probably monoclinic.<sup>38</sup>  $H. = 2$ – $2.5$ .  $G. = 1.75$ .  $Z = b$ ,  $Y \wedge c = 13^\circ$ .  $(- )2V = 52^\circ$ , with weak dispersion. The optic angle may be very small.  $N_x = 1.430$ ,  $N_y = 1.452$ ,  $N_z = 1.458$ ,  $N_z - N_x = 0.028$ . Colorless.

**OCCUR.** Kalinite is more common in nature than potassalumite. It effloresces on clay and alum shales. Tschermigite is found in mines in Bohemia; in shale in Wyoming; it is manufactured extensively at gas works. Potassalumite is found about volcanoes, in caves, etc. A sample with 63.5%  $NH_4$  and 37.5% K has  $G. = 1.68$ .

**Voltaite**  $[K_2(Mg,Fe)_5(Fe,Al)_4(SO_4)_{12} \cdot 18H_2O]$  is isometric; space group<sup>39</sup> probably  $Fm3m$ ;  $a$  27.33; U.C. 20. Crystals dodecahedral or octahedral; usually massive.  $H. = 3$ – $4$ .  $G. = 2.65$ ; 2.79. Partly soluble in water. Isotropic with  $N = 1.594$  (Lausen<sup>40</sup>), 1.602 (Larsen<sup>41</sup>), 1.608 (Bandy<sup>42</sup>). Another phase (?) is tetragonal with  $c$  nearly  $= 1$ ; it is uniaxial negative (in fourlings) according to Gossner;<sup>40</sup>  $(- )2V =$  small,  $N = 1.595$ ,  $N_z - N_x = 0.002$  (Creveling<sup>41</sup>);  $(+ )2V = 50^\circ$ ,  $N = 1.593$  (Mélou<sup>42</sup>). Color oil green, black. Pale green in section. Found in pyrite veins at Alcaparrosa, Chile; also as a result of fire at the United Verde mine in Arizona; also around volcanoes, etc.

**Retgersite**<sup>43</sup>  $(NiSO_4 \cdot 6H_2O)$  is tetragonal trapezohedral with  $c/a = 2.69$ . Crystals short prismatic to fibrous with perfect basal cleavage. Uniaxial negative with

<sup>36</sup> H. P. Klug and L. Alexander: *Jour. Am. Chem. Soc.*, LXII, 1492 (1940).

<sup>37</sup> H. P. Klug: *Jour. Am. Chem. Soc.*, LXII, 2992 and 2993 (1940).

<sup>38</sup> C. A. Beavers and H. Lipson: *Nature*, CXXXIV, 327 (1934); *Min. Abst.*, VI, 182 (1935).

<sup>39</sup> B. Gossner and M. Arm: *Zeit. Krist.*, LXXII, 202 (1929).

<sup>40</sup> B. Gossner and T. Bauerlein: *N. Jahrb. Min.*, Bl. Bd. A, LXVI, 1 (1933).

<sup>41</sup> W. Lindgren and J. G. Creveling: *Econ. Geol.*, XXIII, 233 (1928).

<sup>42</sup> J. Mélou and J. D. H. Donnay: *Min. Abst.*, VI, 361 (1936).

<sup>43</sup> C. Frondel and C. Palache: *Bull. Geol. Soc. Am.*, LIX, 1323 (1948).



$N_O = 1.510$ ,  $N_E = 1.486$ ,  $N_O - N_E = 0.024$ . Color blue-green. Found at the Gap nickel mine, Lancaster County, Pennsylvania; also at Minasragra, Peru; rare.

**Serpierite** [(Cu,Zn,Ca)SO<sub>4</sub>·3H<sub>2</sub>O] is orthorhombic with  $a:b:c = 0.859:1:1.364$ . Crystals tabular with perfect 001 cleavage.  $G. = 2.52$ . The optic plane is 100;  $X = c$ .  $(- )2V = 35^\circ$ ,  $r > v$  strong.  $N_X = 1.584$ ,  $N_Y = 1.642$ ,  $N_Z = 1.647$ ,  $N_Z - N_X = 0.063$ . Color bluish green; pleochroic with  $X =$  pale greenish,  $Y$  and  $Z =$  deep greenish blue. Found on smithsonite at Laurium, Greece.

**Teineite** [Cu(Te,S)O<sub>4</sub>·2H<sub>2</sub>O] is orthorhombic <sup>44</sup> prismatic with  $a:b:c = 0.705:1:0.786$ . Crystals acicular with {010}, {100}, {011}. Good 010 cleavage.  $H. = 2.5$ .  $G. = 3.80$ .  $F. = 2$ . The optic plane is 010;  $X = a$ .  $(- )2V = 36^\circ$ ,  $N_X = 1.767$ ,  $N_Y = 1.782$ ,  $N_Z = 1.791$ ,  $N_Z - N_X = 0.024$ . Color blue with  $X =$  greenish blue,  $Y =$  blue,  $Z =$  indigo blue. Found in the oxide zone of the Teine copper mine in Japan.

**Rhombochase** <sup>10</sup> [HFe(SO<sub>4</sub>)<sub>2</sub>·4H<sub>2</sub>O] is orthorhombic dipyrmidal with  $a:b:c = 0.558:1:0.937$ . Crystals platy with perfect 001 and distinct 110 cleavages.  $H. = 2$ .  $G. = 2.23$ . Slowly soluble in water. The optic plane is 100;  $X = c$ .  $(+ )2V = 27^\circ$ ,  $N_Z = 1.638$ ,  $N_Y = 1.553$ ,  $N_X = 1.534$ ,  $N_Z - N_X = 0.104$ . Colorless to gray or red; red crystals have  $X =$  purple red,  $Y = Z =$  very clear yellow, colorless, or pink. Loses water in stages over sulfuric acid. Deliquesces in moist air. Found in Hungary and Chile.

**EPSOMITE** ORTHORH. DISPHENOIDAL  $a:b:c$  <sup>45</sup>  $= 0.990:1:0.571$  MgSO<sub>4</sub>·7H<sub>2</sub>O

**GOSLARITE** ORTHORH. DISPHENOIDAL  $a:b:c$  <sup>46</sup>  $= 0.981:1:0.563$  ZnSO<sub>4</sub>·7H<sub>2</sub>O

**MORENOSITE** ORTHORH. DISPHENOIDAL  $a:b:c$  <sup>46</sup>  $= 0.982:1:0.566$  NiSO<sub>4</sub>·7H<sub>2</sub>O

**COMP.** Nearly pure end-members are common in nature; a complete artificial series <sup>46</sup> is known from MgSO<sub>4</sub>·7H<sub>2</sub>O to ZnSO<sub>4</sub>·7H<sub>2</sub>O, and also <sup>47</sup> to NiSO<sub>4</sub>·7H<sub>2</sub>O.

**STRUC.** Space group  $P2_12_12_1$ ; for epsomite <sup>45</sup>  $a$  11.94,  $b$  12.03,  $c$  6.86 Å; for goslarite <sup>45</sup>  $a$  11.85,  $b$  12.09,  $c$  6.83; for morenosite <sup>45</sup>  $a$  11.86,  $b$  12.08,  $c$  6.81 Å. U.C. 4.

**PHYS. CHAR.** Crystals prismatic to acicular; commonly massive, fibrous. Perfect 010 cleavage; epsomite has distinct 011 cleavage.  $H. = 2-2.5$ .  $G. = 1.77$  (epsomite); 1.97 (goslarite); 2.00 (morenosite). Soluble in water; taste astringent. Dehydrates to about 6H<sub>2</sub>O in dry air.

**OPT. PROP.** The optic plane is 001;  $X = b$ . See Figs. 97-99.

	$(- )2V$	$r > v$	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$	$F-C (N_Y)$
Epsomite	51° 35'	Weak	1.4326	1.4554	1.4609	0.0283	0.0079
Mg:Zn <sup>48</sup> = 46:54			1.447		1.470	0.023	
Goslarite	46° 14'	Weak	1.4568	1.4801	1.4836	0.0268	0.0084
Mg:Ni <sup>49</sup> = 43:57	47°		1.447	1.470	1.473	0.026	
Morenosite	41° 54'	Marked	1.469	1.489	1.492	0.023	0.009 calc.

<sup>44</sup> T. Yosimura: *Am. Mineral.*, XXIV, 658 (1939); *Jour. Fac. Sci. Hokkaido Univ.*, Series IV, No. 3, 4, 465 (1939).

<sup>45</sup> W. H. Barnes and R. G. Hunter: *Nature*, CXXX, 96 (1932).

<sup>46</sup> H. G. K. Westenbrink: *Proc. Sect. Sci. K. Wet. Ak. Amsterdam*, XXIX, 1223 and 1374 (1926).

<sup>47</sup> H. Dufet: *Bull. Soc. Min. Fr.*, I, 58 (1878).

<sup>48</sup> C. Milton and W. D. Johnston: *Econ. Geol.*, XXXIII, 749 (1938).

<sup>49</sup> C. O. Hutton: *Am. Mineral.*, XXXII, 553 (1947).

Color white or stained; but morenosite is apple green or greenish white.

**INVER.** An artificial monoclinic phase of  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$  (with  $G = 1.691$ ) is isomorphous with melanterite; the stability relations are unknown.

**OCCUR.** Epsomite is found as capillary coatings in caves and mine galleries; also in gypsum quarries near Paris; in anthracite; in thin layers with carnallite in salt

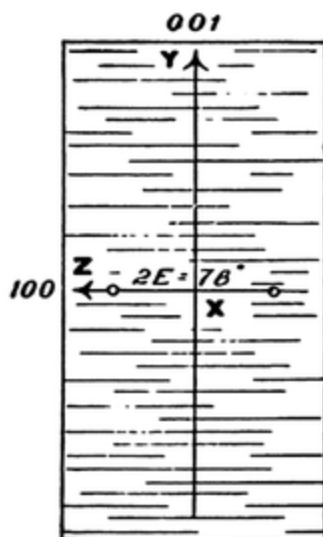


FIG. 97. The optic orientation of epsomite.

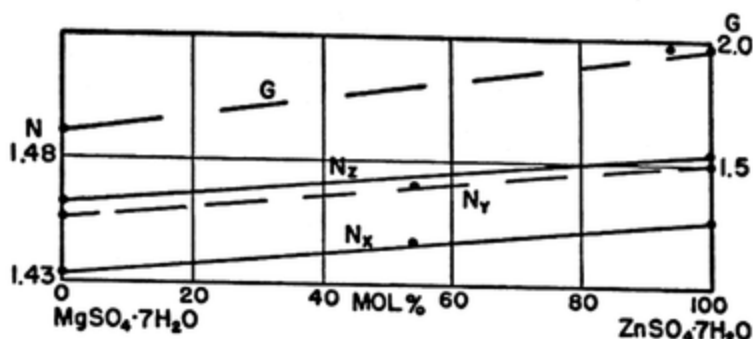


FIG. 98. Properties of the epsomite-goslarite series.

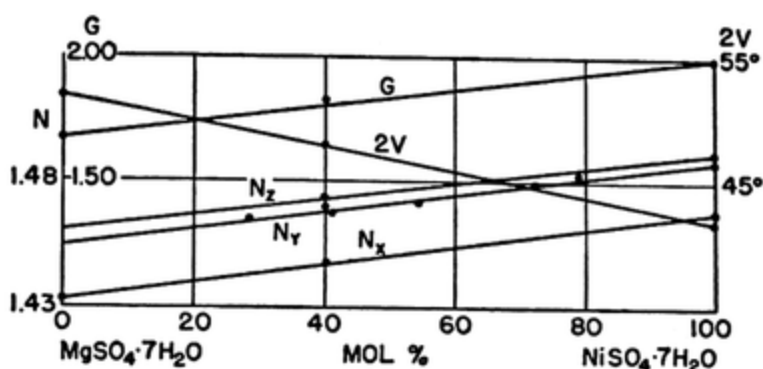


FIG. 99. Properties of the epsomite-morenosite series. See C. O. Hutton: *Am. Mineral.*, XXXII, 553 (1947).

deposits, etc. Goslarite is formed by oxidation and hydration of sphalerite in mines. Morenosite is found as an efflorescence on nickel sulfide ores.

**DIAG.** Epsomite is distinguished by its bitter taste and marked negative relief. Pickeringite is similar, but gives microchemical tests for aluminum and has inclined extinction and weak birefringence.

**Kieserite** ( $\text{MgSO}_4 \cdot \text{H}_2\text{O}$ ) is monoclinic prismatic with  $a:b:c = 0.896:1:0.978$ ,  $\beta = 116^\circ 5.5'$ . Space group  $C2/c$ ;  $a$  6.89,  $b$  7.69,  $c$  7.52 Å. U.C. 4. Crystals pyramidal or prismatic with perfect 110 and 111 cleavages.  $H. = 3.5$ .  $G. = 2.57$ .  $F. = 2-3$ . Slowly soluble in water. The optic plane is 010;  $Z \wedge c = -76^\circ$ , with dispersion.  $(+)2V = 57^\circ$ ,  $r > v$  distinct.  $N_x = 1.523$ ,  $N_y = 1.535$ ,  $N_z = 1.586$ ,  $N_z - N_x = 0.063$ . Color white or stained. Abundant in salt beds at Stassfurt, Germany, etc., with carnallite and gypsum. Mode of occurrence and many cleavages are distinctive.

**Szomolnokite** ( $\text{FeSO}_4 \cdot \text{H}_2\text{O}$ ) is monoclinic prismatic<sup>10</sup> with  $a:b:c = 0.934:1:1.809$ ,  $\beta = 91^\circ 22.5'$ . Crystals pyramidal or {111} tablets, often twinned.  $H. = 2.5$ .

<sup>10</sup> G. Weinert: *N. Jahrb. Min.*, Bl. Bd., LXXV, 297 (1939); *Naturwiss.*, XXVI, 410 (1938). In another setting  $a:b:c = 0.896:1:1.756$ ,  $\beta = 91^\circ 7.5'$ , which shows the isomorphism with szomolnokite.

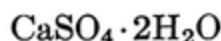
G. = 3.05. Slowly soluble in  $H_2O$ . The optic plane is 010;  $X \wedge c = -26^\circ$ . (+)2V =  $80^\circ$ ,  $r > v$  strong.  $N_X = 1.591$ ,  $N_Y = 1.623$ ,  $N_Z = 1.663$ ,  $N_Z - N_X = 0.072$ . Closely related to kieserite. Found in northern Chile, Utah, etc.

**Szmikite** ( $MnSO_4 \cdot H_2O$ ) is probably monoclinic; one perfect cleavage. H. = 1.5. G. = 3.15. F. = 7. Soluble in water. The optic plane and Z are normal to 010;  $Y \wedge c$  varies notably with the wave length. Negative elongation.  $N_X = 1.57$ ,  $N_Y = ?$ ,  $N_Z = 1.62$ ,  $N_Z - N_X = 0.05$ . An artificial crystal gave: <sup>61</sup> (+)2V = nearly  $90^\circ$ ,  $N_X = 1.562$ ,  $N_Y = 1.595$ ,  $N_Z = 1.632$ ,  $N_Z - N_X = 0.070$ . Color white to pale rose; chalky. Alters easily. Found at Felsöbánya, Hungary.

**Krausite** <sup>62</sup> [ $KFe(SO_4)_2 \cdot H_2O$ ] is monoclinic with  $a:b:c = 1.54:1:1.758$ ,  $\beta = 102^\circ 44'$ . Crystals acicular prismatic to basal tablets with perfect 001 and distinct 100 cleavages. H. = 2.5. G. = 2.84. Soluble in HCl. The optic plane and Z are normal to 010;  $X \wedge c = +35^\circ$ . (+)2V = very large.  $N_X = 1.588$ ,  $N_Y = 1.650$ ,  $N_Z = 1.722$ ,  $N_Z - N_X = 0.134$ . Color pale yellowish green and pleochroic in thicker grains with X = colorless, Y and Z = pale yellow. Found in borax deposits at Borate, California.

## GYPSUM

### MONOCLINIC PRISMATIC



$$a:b:c = 0.6899:1:0.4124 \quad \beta = 99^\circ 18'$$

STRUC. Space group <sup>63</sup>  $C2/c$ ;  $a$  10.47,  $b$  15.15,  $c$  6.28 Å,  $\beta = 98^\circ 58'$ ; U.C. 8.

PHYS. CHAR. Crystals usually simple in habit, commonly tabular parallel to 010 or prismatic to acicular parallel to  $c$ ; also massive, foliated, or granular. Twinning common on 100 as arrowhead forms; also on 101. See Fig. 100. Perfect 010 and imperfect 100 and  $\bar{1}11$  cleavages. H. = 2. G. = 2.32. F. = 2.5–3. Soluble in HCl.

OPT. PROP. At ordinary temperatures the optic plane is parallel with 010 and the positive acute bisectrix Z makes an angle of  $52^\circ 30'$  with  $c$  in the obtuse angle  $\beta$ . See Fig. 101. The optic angle varies rapidly with the temperature; 2E is about  $92^\circ$  at  $20^\circ C$ .; it becomes  $0^\circ$  at about  $91^\circ C$ ., and at higher temperatures the optic axes open out in a plane normal to 010; at the same time the dispersion changes from  $r > v$  with strong inclined dispersion at  $20^\circ C$ . to  $r < v$  with horizontal dispersion at  $120^\circ C$ .

(+)2V =  $58^\circ 5'$  Na,  $N_X = 1.521$ ,  $N_Y = 1.523$ ,  $N_Z = 1.530$ ,  $N_Z - N_X = 0.009$ , F – C for  $N_Y = 0.0078$ .

Gypsum is white or stained; colorless in section.

ALTER. On heating, gypsum loses three-fourths of its water at  $128^\circ C$ . (forming *plaster of Paris*) and the remainder at  $163^\circ C$ . when

<sup>61</sup> E. S. Larsen and M. L. Glenn: *Am. Jour. Sci.*, CC, 225 (1920).

<sup>62</sup> W. F. Foshag: *Am. Mineral.*, XVI, 352 (1931).

<sup>63</sup> E. Onorato: *Zeit. Krist.*, LXXI, 277 (1929). The smallest unit cell has  $a$  10.47,  $b$  15.15,  $c$  6.51 Å,  $\beta = 151^\circ 33'$ , and contains  $4CaSO_4 \cdot 2H_2O$ . See W. A. Wooster: *Zeit. Krist.*, XCIV, 375 (1936). DeJong and Bouman: *Zeit. Krist.*, C, 275 (1938) give  $a$  5.63,  $b$  15.15,  $c$  6.23 Å,  $\beta = 113^\circ 50'$  with new crystal axes.

it becomes "deadburned"; such material has  $N_O = 1.50$ ,  $N_E = 1.56$ ,  $N_E - N_O = 0.06$ . In nature, gypsum may be dehydrated to anhydrite, or even reduced to sulfur.  $\text{CaSO}_4 \cdot 0.5\text{H}_2\text{O}$  is dimorphous; <sup>54</sup> the  $\alpha$ -phase has  $N_X = 1.559$  and  $N_Z = 1.583$ ,  $N_Z - N_X = 0.024$ . The  $\beta$ -phase has  $N_X = 1.550$ ,  $N_Z = 1.556$ ,  $N_Z - N_X = 0.006$ . Colorless. Not rare in thin sections of rocks containing gypsum because the grinding of the section may produce heat enough to partially dehydrate the gypsum.<sup>55</sup>

**OCCUR.** Gypsum forms extensive beds in some places in sedimentary rocks, especially with limestone. It is often associated with halite as

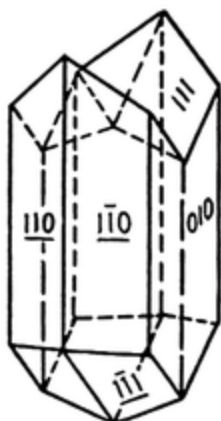


FIG. 100. Gypsum crystal twinned on 100.

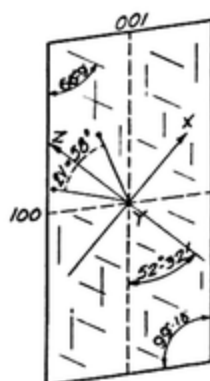


FIG. 101. The optic orientation of gypsum.

a product of evaporation of salt lakes, estuaries, etc. It is also found about volcanoes, the gases of fumaroles reacting with the lime of lavas or other rocks to produce it. It is formed by the decomposition of sulfides, such as pyrite, in the presence of lime. In igneous rocks it is a rare secondary mineral.

**DIAG.** Gypsum has characteristic crystal forms, one perfect and two imperfect cleavages, is soft and hydrous, and has slight negative relief, weak birefringence, and strong inclined dispersion about the positive bisectrix of the medium optic angle.

**Hexahydrate** <sup>56</sup> ( $\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$ ) is monoclinic with  $a:b:c = 1.402:1:1.695$ ,  $\beta = 98^\circ 14'$ . Crystals prismatic, with 110 cleavage.  $G. = 1.75$ .  $F. = 7$ , but

<sup>54</sup> L. G. Berg and V. N. Sveshnikova: *Min. Abst.*, X, 464 (1949). See also C. Gaudefroy: *Bull. Soc. Fr. Minéral.*, XLII, 284 (1919).  $\alpha$ - $\text{CaSO}_4 \cdot 0.5\text{H}_2\text{O}$  has been found in arid parts of Central Asia; see V. I. Popov and A. L. Vorob'ev: *Chem. Abst.*, XLIII, 2897 (1949).

<sup>55</sup> C. Milton: *Am. Mineral.*, XXVII, 517 (1942).

<sup>56</sup> W. D. Dobrovolsky: *Mém. Soc. Russe Minéral.*, LVIII, 3 (1923); *N. Jahrb. Min.*, I, 142 (1930).

exfoliates. The optic plane is 010;  $X \wedge c = +25^\circ$ ;  $X$  nearly normal to  $\bar{1}02$ .  $(- )2V = 38^\circ$ ,  $r > v$ .  $N_X = 1.426$ ,  $N_Y = 1.453$ ,  $N_Z = 1.456$ ,  $N_Z - N_X = 0.030$ . Found in salt lake deposits, as in the Lillooet District, British Columbia.

**Bianchite**<sup>57</sup>  $[(Zn,Fe)SO_4 \cdot 6H_2O]$  with  $Zn:Fe = 2:1$  is monoclinic with  $a:b:c = 1.379:1:1.666$ ,  $\beta = 98^\circ 30'$ ; it belongs to a  $6H_2O$  series of salts of  $Mg$ ,  $Zn$ ,  $Fe$ ,  $Ni$ , and  $Co$ .  $G. = 2.03$ . The optic plane is 010;  $X \wedge c = -26^\circ$ .  $(- )2V = 15^\circ-16^\circ$ ,  $r > v$  weak.  $N_X = 1.465$ ,  $N_Y = 1.494$ ,  $N_Z = 1.495$ ,  $N_Z - N_X = 0.030$ . Again:<sup>57</sup>  $N_X = 1.462$ ,  $N_Y = 1.489$ ,  $N_Z = 1.490$ ,  $N_Z - N_X = 0.028$ . White. Forms crusts in artificial caves in Trentino. Dehydration forms a stable substance with  $2H_2O$  at  $150^\circ C$ ; all water is lost at  $260^\circ C$ .

**Melanterite**  $[(Fe,Zn,Cu,Co,Mg)SO_4 \cdot 7H_2O]$  is monoclinic<sup>58</sup> with  $a:b:c = 1.18:1:1.537$ ,  $\beta = 104^\circ 23'$ . Space group<sup>59</sup> probably  $P2_1/c$ ;  $a$  15.33,  $b$  6.50,  $c$  20.08 Å; U.C. 8. Crystals tabular or equant with perfect 001 and good 110 cleavages. Often in fibrous crusts.  $H. = 2-3$ .  $G. = 1.9$  ca.  $F. =$  easy. Astringent taste. Dehydrates easily in dry air. The optic plane is 010;  $Z \wedge c = +54^\circ$  to  $+78^\circ$ .  $(+ )2V =$  large with weak dispersion (optically negative<sup>60</sup> and  $G. = 1.82$  with  $35-40 MgSO_4 \cdot 7H_2O$ ).  $N_X = 1.467-1.479$ ,  $N_Y = 1.47-1.48$ ,  $N_Z = 1.478-1.489$ ,  $N_Z - N_X = 0.012-0.015$ . See Fig. 102. Colorless to green (Fe), blue (Cu), carmine (Co). Formed by oxidation and hydration of sulfides in damp air. It may alter to siderotil.

<sup>57</sup> C. Andreatta: *Rend. Accad. Lincei*, XI, 760 (1930); *Am. Mineral.*, XV, 538 (1930); *Min. Abst.*, V, 258 (1933).

<sup>58</sup> E. S. Larsen and M. L. Glenn: *Am. Jour. Sci.*, CC, 225 (1920); E. B. Eckel: *Am. Mineral.*, XVIII, 449 (1933); F. Machatschki: *Min. Abst.*, VI, 142 (1935); G. N. Vertushkov: *Min. Abst.*, VII, 418 (1940); S. G. Gordon: *Min. Abst.*, VIII, 187 (1942).

<sup>59</sup> I. Ness: *Naturw.*, XXVIII, 78 (1940); *Min. Abst.*, VIII, 10 (1941).

<sup>60</sup> J. Kokta: *Min. Abst.*, VII, 316 (1939).

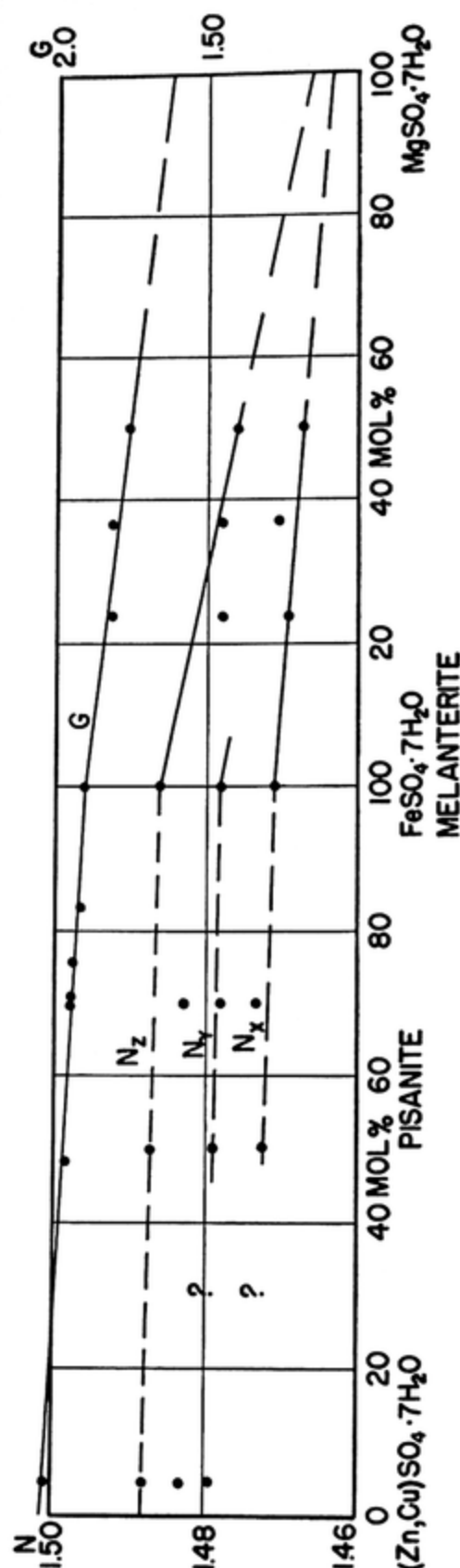


Fig. 102. Properties of melanterite.

**Tamarugite**<sup>61</sup>  $[\text{NaAl}(\text{SO}_4)_2 \cdot 6\text{H}_2\text{O}]$  is monoclinic with  $a:b:c = 0.292:1:0.242$ ,  $\beta = 94^\circ 50'$ . Crystals {010} tablets resembling gypsum. Multiple twinning. Perfect 010 cleavage.  $H. = 1$ .  $G. = 2.1$ .  $F. = 7$ . Soluble in water. The optic plane is 010;  $X \wedge c = 4^\circ$  (Gordon<sup>61</sup>);  $Z = b$  and  $X \wedge c = 60^\circ$  (Larsen<sup>62</sup>);  $(+ )2V = 60^\circ$ ,  $N_Z = 1.484$ ,  $N_Y = 1.487$ ,  $N_X = 1.496$ ,  $N_Z - N_X = 0.012$  (Larsen<sup>62</sup>). Found in Chile and Utah.

**Mendozite** [*Sodium alum*— $\text{NaAl}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$ ] is monoclinic prismatic and pseudo-isometric. The isometric phase<sup>38</sup> (artificial) has  $a$  12.19 Å; U.C. 4. It is isotropic with  $N = 1.439$ . Mendozite is often fibrous.  $H. = 3$ .  $G. = 1.73$ .  $F. = 1$ . Soluble in water.  $X = b$ ;  $Z \wedge$  twinning plane<sup>10</sup>  $= 40^\circ$ ;  $(- )2V = ?$ ,  $N_X = ?$ ,  $N_Y = 1.466$ ,  $N_Z = 1.472$ . Also  $(- )2V =$  very small,  $N_X = 1.434$ ,  $N_Y = 1.455$ ,  $N_Z = 1.456$ ,  $N_Z - N_X = 0.022$ . Colorless. A uniaxial phase is also known with  $N_O = 1.459$ ,  $N_E = 1.431$ ,  $N_O - N_E = 0.028$ . Found in Argentina, Chile, etc.

CHALCANTHITE	TRICLINIC PINACOIDAL <sup>4</sup>	$(\text{Cu, Fe, Mg, Co, Zn, Mn})\text{SO}_4 \cdot 5\text{H}_2\text{O}$			
	$a:b:c$	$\alpha$	$\beta$	$\gamma$	
<b>Chalcantite</b>					
proper	0.572:1:0.557	82° 16'	107° 26'	102° 40'	$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$
Siderotil	0.596:1:0.577	81° 23'	110° 28'	105° 33'	$\text{FeSO}_4 \cdot 5\text{H}_2\text{O}$
<b>Magnesium</b>					
chalcantite	0.602:1:0.561	81° 30'	109° 0'	104° 55'	$\text{MgSO}_4 \cdot 5\text{H}_2\text{O}$
<b>Cobalt chalcantite</b>					$\text{CoSO}_4 \cdot 5\text{H}_2\text{O}$

**COMP.** Natural crystals usually near end-members, but artificial crystals are of all types; a natural crystal known<sup>48</sup> with  $\text{Mg}:\text{Cu}:\text{Zn}:\text{Fe}:\text{Mn} = 50:27:17:5:1$ .

**STRUC.**<sup>62</sup> Space group  $P\bar{1}$ ; for  $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ :  $a$  6.12,  $b$  10.7,  $c$  5.97 Å. U.C. 2.

**PHYS. CHAR.** Crystals commonly flattened parallel to 111, with poor 110,  $1\bar{1}0$ , and 111 cleavages.  $H. = 2.5$ .  $G. = 2.2$  (Cu).  $F. = 3$ . Soluble in water. Taste metallic and nauseous.

**OPT. PROP.** For  $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$  (commonly called *blue vitriol*):  $X$  is between  $-a$ ,  $+b$ , and  $+c$ ; it makes angles of  $81^\circ 30'$ ,  $43^\circ 45'$ , and  $73^\circ$  with normals to 110,  $1\bar{1}0$ , and 111;  $Z$  makes<sup>63</sup> angles of  $46^\circ 45'$ ,  $12^\circ 30'$ , and  $46^\circ 15'$  with normals to the same faces.  $(- )2V = 56^\circ$ ,  $r < v$  weak, with crossed and strong inclined dispersion.  $N_X = 1.516(-1.511)$ ,  $N_Y = 1.539(-1.530)$ ,  $N_Z = 1.546(-1.538)$ ,  $N_Z - N_X = 0.030(-0.027)$ . Color blue of various shades, sometimes greenish. See Figs. 103 and 104.

For  $\text{FeSO}_4 \cdot 5\text{H}_2\text{O}$ :  $(- )2V =$  moderate,  $N_X = 1.528$ ,  $N_Y = 1.537$ ,  $N_Z = 1.545$ ,  $N_Z - N_X = 0.017$ . Color bluish green, pale green, or white.

For  $\text{MgSO}_4 \cdot 5\text{H}_2\text{O}$ :  $G. = 1.72$ ,  $X$  nearly normal<sup>64</sup> to 010.  $(- )2V = 45^\circ$ ,  $r < v$ ,  $N_X = 1.482$ ,  $N_Y = 1.492$ ,  $N_Z = 1.493$ ,  $N_Z - N_X = 0.011$ . Colorless.

For  $\text{CoSO}_4 \cdot 5\text{H}_2\text{O}$ :  $G. = 2.2$ .  $F. = 3$ .  $(- )2V =$  moderate.  $N_X = 1.530$ ,  $N_Y = 1.548$ ,  $N_Z = 1.550$ ,  $N_Z - N_X = 0.020$ . Color rose-pink.

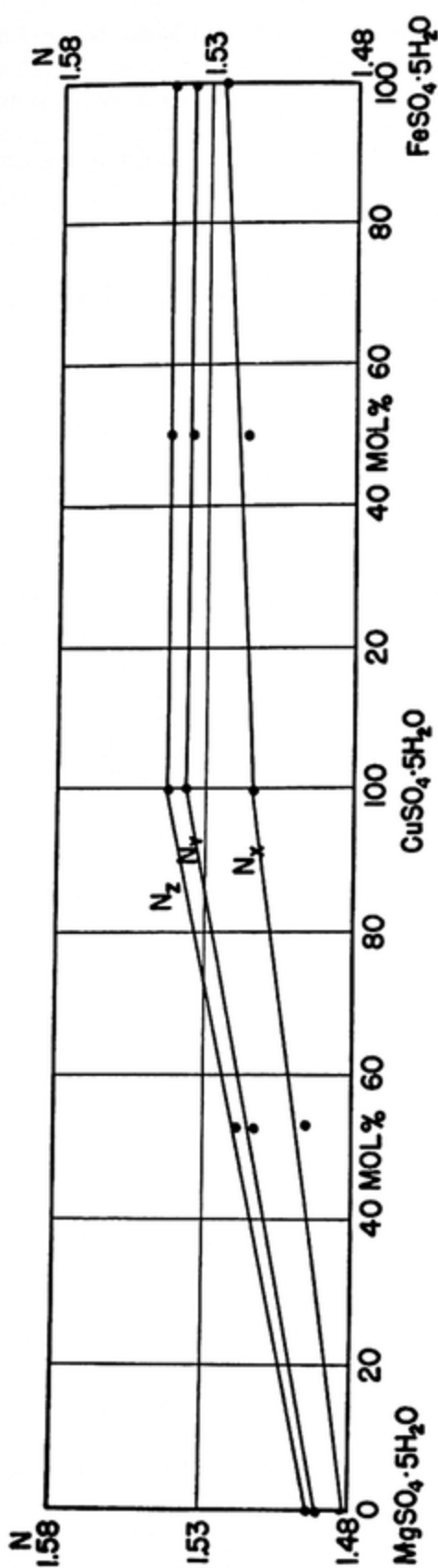
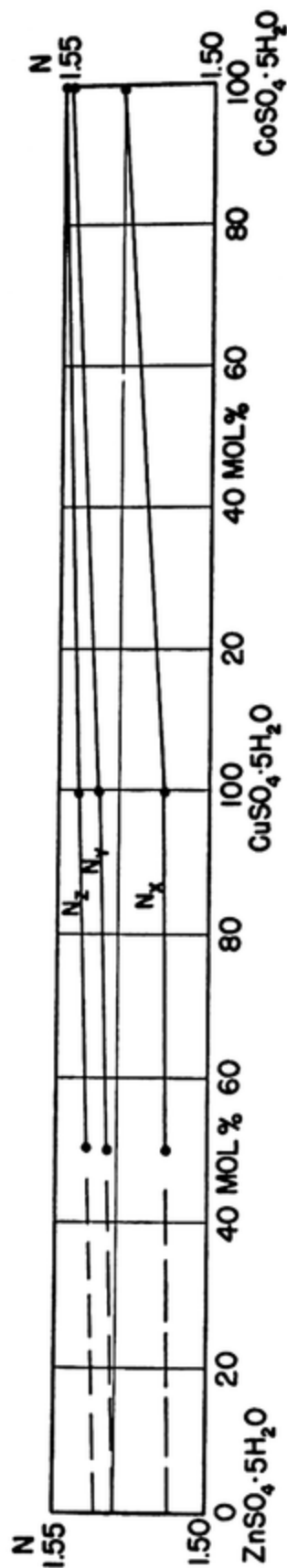
<sup>61</sup> S. G. Gordon: *Not. Nat. Acad. Sci. Phila.*, 57, 1940.

<sup>62</sup> B. Gossner and K. Brückl: *Zeit. Krist.*, LXIX, 422 (1929). C. A. Beevers and H. Lipson: *Min. Abst.*, VI, 181 (1936). T. F. W. Barth and G. Tunell: *Am. Mineral.*, XVIII, 187 (1933).

<sup>63</sup> J. Mélon: *Bull. Soc. Fr. Min.*, XLVII, 141 (1924).

<sup>64</sup> H. L. Robson: *Jour. Am. Chem. Soc.*, XLIX, 2772 (1927).



FIG. 103. Properties of chalcantite ( $\text{MgSO}_4 \cdot 5\text{H}_2\text{O}$ - $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ - $\text{FeSO}_4 \cdot 5\text{H}_2\text{O}$ ).FIG. 104. Properties of chalcantite ( $\text{ZnSO}_4 \cdot 5\text{H}_2\text{O}$ - $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ - $\text{CoSO}_4 \cdot 5\text{H}_2\text{O}$ ).

For <sup>3</sup>  $\text{ZnCu}(\text{SO}_4)_2 \cdot 10\text{H}_2\text{O}$ :  $G. = 2.1$ ,  $N_X = 1.514$ ,  $N_Y = 1.534$ ,  $N_Z = 1.541$ ,  $N_Z - N_X = 0.027$ .

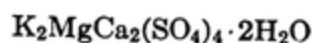
ALTER. Samples which are not compact dehydrate and fall to a white powder when exposed to air.

OCCUR. Formed by oxidation and hydration of sulfide ores. Found in solution in some mine waters.

DIAG. Distinguished by color (except  $\text{MgSO}_4 \cdot 5\text{H}_2\text{O}$ ) and taste.

## POLYHALITE

TRICLINIC PINACOIDAL



$$a:b:c = 0.931:1:0.856, \alpha = 92^\circ 29', \beta = 123^\circ 4', \gamma = 88^\circ 21'$$

PHYS. CHAR. Crystals fibrous parallel to  $b$  or  $\{010\}$  tablets. Lamellar 010 twinning; also a second which may produce a grating. Distinct 100 cleavage.  $H. = 2.5-3$ .  $G. = 2.78$ .  $F. = 1.5$ . Partly soluble in water.

OPT. PROP. The easy cleavage lamella shows multiple twinning with asymmetrical extinctions at  $20^\circ$  and  $29^\circ$ . An optic axis is nearly parallel to the fibers.  $(- )2V = 60^\circ$ ,  $N_X = 1.548$ ,  $N_Y = 1.562$ ,  $N_Z = 1.567$ ,  $N_Z - N_X = 0.019$ . Color flesh red, yellow, brick red; colorless in section.

OCCUR. Polyhalite is important in salt deposits of Prussia, etc.

DIAG. In polyhalite the easy cleavage lamella shows one optic axis just outside the field of view, while in glauberite the easy cleavage is nearly normal to the acute bisectrix.

**Leightonite** <sup>65</sup>  $[\text{K}_2\text{CuCa}_2(\text{SO}_4)_4 \cdot 2\text{H}_2\text{O}]$  is triclinic pinacoidal <sup>66</sup> (pseudo-orthorhombic) with  $a:b:c = 0.704:1:0.458$ , with  $\alpha$ ,  $\beta$ , and  $\gamma$  all near  $90^\circ$ . Multiple twinning on 100 and on 010. Crystals often bladed, with no cleavage.  $H. = 3$ .  $G. = 2.95$ . The optic plane is nearly parallel with 001;  $Y \wedge c = 3^\circ$ ;  $X \wedge b = 3^\circ$  to  $5^\circ$ ;  $Z$  near  $a$ .  $(- )2V = 65^\circ \pm$ ,  $r > v$  moderate.  $N_X = 1.578$ ,  $N_Y = 1.587$ ,  $N_Z = 1.595$ ,  $N_Z - N_X = 0.017$ . Color in mass pale blue. Found with atacamite and kröhnkite at Chuquicamata, Chile.

## (b) WITH ADDITIONAL ANIONS—ANHYDROUS

**Alumian** <sup>67</sup>  $[\text{Al}_2\text{O}(\text{SO}_4)_2]$  is hexagonal; crystals rhombohedral, striated, resembling cubes.  $H. = 2-3$ .  $G. = 2.74$ .  $F. = 7$ . Soluble in acid. Uniaxial positive with  $N_O = 1.583$ ,  $N_E = 1.602$ ,  $N_E - N_O = 0.019$ . White. Found in mines in Spain.

## (b) WITH ADDITIONAL ANIONS—HYDROUS

**Slavikite** <sup>68</sup>  $[\text{MgFe}'''_3(\text{OH})_3(\text{SO}_4)_4 \cdot 18\text{H}_2\text{O}]$  is hexagonal with  $c/a = 1.389$ . *Franquenite* <sup>69</sup> is probably a synonym. Tiny crystals rhombohedral with  $\{10\bar{1}1\}$  and

<sup>65</sup> C. Palache: *Am. Mineral.*, XXIII, 34 (1938).

<sup>66</sup> Leightonite is a homologue of polyhalite. See M. A. Peacock: *Am. Mineral.*, XXIII, 38 (1938).

<sup>67</sup> S. G. Gordon: *Not. Nat. Acad. Sci. Phila.*, 57, 1940, suggests that  $\text{Na}_2\text{O}$  has been overlooked in "alumian," and that it is actually natroalumite.

<sup>68</sup> S. G. Gordon: *Not. Nat. Acad. Sci. Phila.*, 89, 1941. R. Rost (*Min. Abst.*, IX, 204, 1946) argues that slavikite has the composition  $\text{Fe}_2\text{OH}(\text{SO}_4)_2 \cdot 4\text{H}_2\text{O}$ .

<sup>69</sup> R. Van Tassel: *Min. Abst.*, IX, 125 (1945).

{0001}.  $G. = 1.99$ . Uniaxial negative with  $N_O = 1.533$ ,  $N_E = 1.497$ ,  $N_O - N_E = 0.036$ . Greenish yellow with  $O =$  lemon yellow,  $E =$  colorless. Alteration product of pyrite; found at Alcaparrosa, Argentina, and in Bohemia.

**Metavoltine**<sup>10</sup>  $[Na_3KFe_3OH(SO_4)_6 \cdot 10H_2O]$  is hexagonal dipyramidal with  $c/a = 0.947$ . Space group  $C6/m$  or  $C6_3m$ . Crystals six-sided plates with perfect basal cleavage.  $H. = 2.5$ .  $G. = 2.5$ .  $F. = 5$ . Partly soluble in water. Uniaxial negative with  $N_O = 1.589-1.590$ ,  $N_E = 1.572-1.574$ ,  $N_O - N_E = 0.016-0.017$ . Again: <sup>70</sup>  $N_O = 1.595$ ,  $N_E = 1.581$ ,  $N_O - N_E = 0.014$ . Color olive green to greenish brown with  $O =$  brown,  $E =$  pale greenish yellow. Found with metasideronatrium at Chuquicamata, Chile. The same mineral (?) without Na and with less  $H_2O$  occurs at Vesuvius<sup>71</sup> and has been made artificially.<sup>72</sup> It has  $a$  19.43,  $c$  18.60 Å. and  $a:c = 1:0.957$ .  $G. = 2.4$ . Uniaxial negative with  $N_O = 1.591$ ,  $N_E = 1.573$ ,  $N_O - N_E = 0.018$ . Color yellow with  $O =$  deep orange yellow,  $E =$  pale yellow to nearly colorless. Found with voltaite and pyrite in trachyte, etc.

A similar mineral<sup>73</sup> called  $\beta$ -metavoltine  $[K_5Fe''Fe_2'''O(SO_4)_6 \cdot 9H_2O]$  is pseudohexagonal and monoclinic with  $a$  9.4 (or 18.8?),  $b$  18.65,  $c$  9.4 Å,  $\beta = 120^\circ$ . Perfect 010 cleavage.  $X = b$ ;  $Z \wedge c = 80^\circ$ .  $(- )2E = 73^\circ \pm$ .

**Ferritungstite**<sup>74</sup>  $[Fe(OH)_4WO_4 \cdot 4H_2O]$  is hexagonal, tabular to fibrous. Decomposed by acid. Uniaxial negative with  $N_O = 1.80$ ,  $N_E = 1.72$ ,  $N_O - N_E = 0.08$  (Larsen<sup>3</sup>). Fibers have positive elongation. Color pale yellow. Found in ore deposits in Washington as an alteration product of wolframite.

**Parabutlerite**<sup>10</sup>  $(Fe'''OH SO_4 \cdot 2H_2O)$  is orthorhombic dipyramidal with  $a:b:c = 0.731:1:0.722$ . Crystals prismatic with poor 110 cleavage.  $H. = 2.5$ .  $G. = 2.55$ . The optic plane is 001;  $Z = a$ .  $(+)2V = 87^\circ$ ,  $r > v$  moderate.  $N_X = 1.598$ ,  $N_Y = 1.663$ ,  $N_Z = 1.737$ ,  $N_Z - N_X = 0.139$ . Again: <sup>75</sup>  $(-)2E = 76^\circ$ ,  $N_X = 1.589$ ,  $N_Y = 1.660$ ,  $N_Z = 1.750$ ,  $N_Z - N_X = 0.161$ . Color orange with  $X =$  pale yellow,  $Y =$  greenish yellow,  $Z =$  brownish yellow. Found in Chile with copiapite, jarosite, etc.

**Fibroferrite**  $[Fe_2'''(OH)_2(SO_4)_2 \cdot 9H_2O]$  is orthorhombic with <sup>76</sup>  $a:b:c = 0.560:1:0.216$ . Minute fibers parallel to  $c$ . Perfect 001 cleavage.  $H. = 2-2.5$ .  $G. = 2.52$ .  $F. = 4.5-5$ . Soluble in water.  $Z = c$ .  $(+)2V =$  nearly  $0^\circ$ ,  $N_X = 1.533$  (1.525),  $N_Y = 1.534$ ,  $N_Z = 1.575$  (1.565),  $N_Z - N_X = 0.042$  (0.040) (Larsen<sup>3</sup>);  $N_X = 1.513$ ,  $N_Y = 1.535$ ,  $N_Z = 1.571$ ,  $N_Z - N_X = 0.058$  (Bandy<sup>77</sup>). Color pale yellow with  $X$  and  $Y =$  nearly colorless,  $Z =$  pale yellow. Found as an alteration product in mines in Chile, etc.

<sup>70</sup> S. G. Gordon: *Not. Nat. Acad. Sci. Phila.*, 64, 1940.

<sup>71</sup> F. Zambonini: *Atti. Accad. Napoli*, 8, XIII (1906).

<sup>72</sup> R. Scharizer: *Zeit. Krist.*, LVIII, 420 (1923); B. Gossner and M. Arm: *Zeit. Krist.*, LXXII, 205 (1929).

<sup>73</sup> B. Gossner: *Cent. Min.*, 1936A, 262.

<sup>74</sup> W. T. Schaller: *Zeit. Krist.*, L, 112 (1912).

<sup>75</sup> S. G. Gordon: *Not. Nat. Acad. Sci. Phila.*, 89, 1941. The optic angle and sign are inconsistent with the indices. With the cleavage as 101 Gordon gets  $a:b:c = 1.357:1:0.978$ , but this makes  $a > b$ .

<sup>76</sup> S. G. Gordon: *Not. Nat. Acad. Sci. Phila.*, 102, 1942.

<sup>77</sup> M. C. Bandy: *Am. Mineral.*, XXIII, 669 (1938). F. Ulrich in *N. J. Min.*, I, 232 (1937), describes fibroferrite as uniaxial with  $N_O = 1.631$  and  $N_E = 1.566$ .

**Lapparentite**<sup>78</sup>  $[\text{Al}_2(\text{OH})_2(\text{SO}_4)_2 \cdot 9\text{H}_2\text{O}]$  forms rhombic tablets with diagonal extinction.  $H. = 3$ .  $G. = 1.89$ . Acute bisectrix normal to tabular face.  $X \wedge c = +5^\circ$ .  $(+)2V = 80^\circ$  (calc).  $N_X = 1.460$ ,  $N_Y = 1.470$ ,  $N_Z = 1.484$ ,  $N_Z - N_X = 0.024$ . Colorless. Formed during the burning of a coal dump.

**Guildite**  $[\text{Cu}_3\text{Fe}_4'''(\text{OH})_4(\text{SO}_4)_7 \cdot 15\text{H}_2\text{O}]$  is monoclinic with  $a:b:c = 1.037:1:1.407$ ,  $\beta = 105^\circ 17'$ . Crystals roughly cubic. Perfect 001 and 100 cleavages.  $H. = 2.5$ .  $G. = 2.72$ .  $(+)2V = \text{small}$ .  $N_X = 1.623$ ,  $N_Y = 1.630$ ,  $N_Z = 1.684$ ,  $N_Z - N_X = 0.061$ . Color brown in mass; pleochroic with  $X = Y = \text{pale yellow}$ ,  $Z = \text{greenish yellow}$ . Produced by a fire in the United Verde mine, Arizona.

**Botryogen**<sup>10</sup>  $[\text{MgFe}(\text{OH})(\text{SO}_4)_2 \cdot 7\text{H}_2\text{O}]$  is monoclinic prismatic,  $a:b:c = 0.589:1:0.3996$ ,  $\beta = 100^\circ 1'$ . Crystals prismatic, with perfect 010 and poor 110 cleavages.  $H. = 2-2.5$ .  $G. = 2.1$ .  $F. = 4.5-5$ . Soluble in HCl. The optic plane and  $X$  are normal to 010;  $Z \wedge c = +12^\circ$ .  $(+)2V = 42^\circ$ ,  $r > v$  strong.  $N_X = 1.523$ ,  $N_Y = 1.530$ ,  $N_Z = 1.582$ ,  $N_Z - N_X = 0.059$ . Again:  $(+)2V = 41^\circ$ ,  $r < v$ ,  $N_X = 1.544$ ,  $N_Y = 1.548$ ,  $N_Z = 1.572$ ,  $N_Z - N_X = 0.028$ . Color red to yellow with  $X = \text{bright yellow}$ ,  $Y = \text{pale red}$ ,  $Z = \text{deep orange red}$ . Again:<sup>10</sup>  $X = \text{colorless to pale brown}$ ,  $Y = \text{cinnamon brown}$ ,  $Z = \text{golden yellow}$ . Found in mines in Chile, etc.

**Butlerite**<sup>79</sup>  $(\text{FeOH}\text{SO}_4 \cdot 2\text{H}_2\text{O})$  is monoclinic with  $a:b:c = 0.875:1:0.790$ ,  $\beta = 108^\circ 35'$ . Crystals pyramidal with perfect 100 cleavage.  $H. = 2.5$ .  $G. = 2.55$ . The optic plane is normal to 010;  $X \wedge c = 18^\circ$ .  $(+)2V = \text{large}$ .  $N_X = 1.593$ ,  $N_Y = 1.665$ ,  $N_Z = 1.741$ ,  $N_Z - N_X = 0.148$  (Gordon<sup>79</sup>). Again:  $(-)2V = \text{large}$ ,  $N_X = 1.604$ ,  $N_Y = 1.674$ ,  $N_Z = 1.731$ ,  $N_Z - N_X = 0.127$  (Lausen<sup>80</sup>). Color orange in mass; pleochroic with  $X = \text{pale brownish yellow}$ ,  $Y = \text{pale yellow}$ ,  $Z = \text{pale canary yellow}$ . Produced by a fire in the United Verde mine, Arizona.

**Quetenite**  $[\text{MgFe}_2'''(\text{OH})_2(\text{SO}_4)_3 \cdot 12\text{H}_2\text{O}]$  is monoclinic with distinct prismatic cleavage.  $H. = 3$ .  $G. = 2.12$ .  $F. = 4.5-5$ . Partly soluble in water.  $(+)2V = 34^\circ$ ,  $r > v$  distinct.  $N_X = 1.530$ ,  $N_Y = 1.535$ ,  $N_Z = 1.582$ ,  $N_Z - N_X = 0.052$ . Color pale reddish brown with  $X$  and  $Y = \text{colorless}$ ,  $z = \text{orange-yellow to brown}$ . Found with chalcantite. Possibly the same as botryogen.<sup>10</sup>

**Hohmannite**<sup>81</sup>  $[\text{Fe}_2(\text{OH})_2(\text{SO}_4)_2 \cdot 7\text{H}_2\text{O}]$  is triclinic with  $a:b:c = 0.726:1:0.895$ ,  $\alpha = 89^\circ 50'$ ,  $\beta = 91^\circ 10'$ ,  $\gamma = 78^\circ 46'$ . Crystals basal tablets or prismatic with perfect 010 and distinct 110 and  $\bar{1}\bar{1}0$  cleavages. Loses  $4\text{H}_2\text{O}$  (and becomes *metahohmannite*) very quickly in air.  $G. = 2.2$ .  $F. = 5$ . Soluble in HCl. An optic axis nearly normal to 010 cleavage. In 010,  $X' \wedge c = 22^\circ$ .  $(-)2V = 40^\circ$ ,  $r > v$  extreme.  $N_X = 1.553$ ,  $N_Y = 1.643$ ,  $N_Z = 1.657$ ,  $N_Z - N_X = 0.104$ . Color red to brown, with  $X = \text{very pale yellow}$ ,  $Y = \text{pale greenish yellow}$ ,  $Z = \text{dark greenish brown or brownish red}$ . Found in ore deposits in Chile.

**Metahohmannite**<sup>81</sup>  $[\text{Fe}_2(\text{OH})_2(\text{SO}_4)_2 \cdot 3\text{H}_2\text{O}]$  is granular.  $(+)2V = 70^\circ$  ca., calc.  $N_X = 1.709$ ,  $N_Y = 1.718$ ,  $N_Z = 1.734$ ,  $N_Z - N_X = 0.025$ . Color reddish yellow, with  $X = \text{pale yellow}$ ,  $Y = \text{reddish yellow}$ ,  $Z = \text{reddish brown}$ . Found in ore deposits in Chile.

**Amarantite**<sup>81</sup>  $(\text{Fe}'''\text{OHSO}_4 \cdot 3\text{H}_2\text{O})$  is triclinic pinacoidal with  $a:b:c = 0.769:1:0.574$ ,  $\alpha = 95^\circ 39'$ ,  $\beta = 90^\circ 24'$ ,  $\gamma = 97^\circ 13'$ . Crystals prismatic, with perfect 100

<sup>78</sup> R. Rost: *Min. Abst.*, VII, 11 (1938); H. Ungemach: *Bull. Soc. Fr. Min.*, LVIII, 209 (1935). S. G. Gordon: *Not. Nat. Acad. Sci. Phila.*, 57, 1940, argues that lapparentite is really tamarugite, but the optic properties are different.

<sup>79</sup> S. G. Gordon: *Not. Nat. Acad. Sci. Phila.*, 89, 1941.

<sup>80</sup> C. Lausen: *Am. Mineral.*, XIII, 203 (1928); originally described as orthorhombic, but said to be triclinic by M. C. Bandy: *Am. Mineral.*, XXIII, 669 (1938).

<sup>81</sup> Hohmannite is called *castanite* by A. F. Rogers: *Am. Mineral.*, XVI, 396 (1931).

and 010 cleavages.  $H. = 2.5$ .  $G. = 2.2$ .  $F. = 4.5-5$ . Soluble in HCl. Axis X nearly normal to 100 in which  $Z' \wedge c = 38^\circ$  from right above to left below.  $Z' \wedge c = -17^\circ$  on 010.  $(- )2V = 28^\circ$ ,  $r < v$  distinct with horizontal dispersion.  $N_X = 1.51$ ,  $N_Y = 1.605$ ,  $N_Z = 1.611$ ,  $N_Z - N_X = 0.10$ . Again:  $N_X = 1.516$ ,  $N_Y = 1.598$ ,  $N_Z = 1.621$ ,  $N_Z - N_X = 0.105$ . Color orange to brownish red with X = colorless, Y = pale orange-yellow, Z = orange-yellow to brownish red. Found in ore deposits in Chile.

### 3. Sulfates with type formula $\approx A_3B_2X_8$

#### (a) WITHOUT ADDITIONAL ANIONS—ANHYDROUS

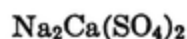
**Langbeinite**  $[K_2Mg_2(SO_4)_3]$  is isometric tetartoidal; <sup>82</sup> space group  $P2_13$ ;  $a$  9.96 Å. U.C. 4. Crystals tetartohedral, modified.  $H. = 3-4$ .  $G. = 2.83$ .  $F. = 2$ . Soluble in water. Absorbs water rapidly in air. Isotropic with  $N = 1.535$ . Colorless. Found in salt beds, etc.

**Manganolangbeinite**  $[K_2Mn_2(SO_4)_3]$  is isometric tetartoidal.  $G. = 3.02$ . Isotropic with  $N = 1.57$ . Found in a cavity in lava at Vesuvius.

**Palmierite**  $(K,Na)_2Pb(SO_4)_2$  is hexagonal scalenohedral with  $c/a = 3.761$ . Space group <sup>83</sup>  $R\bar{3}m$ ;  $a$  5.58,  $c$  20.67. Crystals basal laminae, often hexagonal in outline.  $G. = 4.5$ .  $F. = \text{easy}$ . Soluble in  $HBO_3$ . Decomposed by  $H_2O$ . Uniaxial negative <sup>84</sup> with  $N_O = 1.712$ ,  $N_O - N_E = \text{strong}$ . Again: <sup>85</sup>  $G. = 4.195$ ,  $N_O = 1.7103$ . Colorless. Found at Vesuvius with apthitalite.

#### GLAUBERITE

#### MONOCLINIC PRISMATIC



$$a:b:c = 1.220:1:1.027 \quad \beta = 112^\circ 11'$$

**PHYS. CHAR.** Crystals basal tablets, or prismatic, with perfect 001 and imperfect 110 cleavages.  $H. = 3$ .  $G. = 2.85$ .  $F. = 1.5-2$ . Soluble in HCl. Partly soluble in  $H_2O$ .

**OPT. PROP.** The optic plane is normal to 010 at ordinary temperatures with  $X \wedge c = -30^\circ 46'$  Na. Therefore the basal cleavage is nearly normal to the acute bisectrix. With change of temperature the position of X and Y remains nearly constant, but the optic angle changes rapidly as follows:

C. temp.	5°	22°	36°	46°	58°	85°
Red light (Li)	2E = $16^\circ 6'$	$13^\circ 30'$	$11^\circ 1'$	$8^\circ 40'$	$0^\circ$ (at $52^\circ$ )	$10^\circ 47'$
Yellow (Na)	2E = $14^\circ 8'$	$11^\circ 8'$	$8^\circ 9'$	$0^\circ$ (at $43^\circ$ )	$7^\circ 14'$	$13^\circ 14'$
Green (Tl)	2E = $11^\circ 42'$	$8^\circ 14'$	$0^\circ$	$7^\circ 8'$	$10^\circ 32'$	$15^\circ 15'$
Blue	2E = $8^\circ 51'$	$0^\circ$ (at $18^\circ$ )	$8^\circ 42'$	$11^\circ 8'$	$13^\circ 2'$	$17^\circ 7'$

At  $5^\circ$  C. the optic plane is normal to 010 for all colors; at  $85^\circ$  C. it is parallel to 010 for all colors. At the same time the dispersion changes from horizontal with  $r > v$  to inclined with  $r < v$ ; the dispersion is very strong, giving abnormal interference figures in white light.

$(- )2E = 0^\circ-17^\circ$ ,  $N_X = 1.515$ ,  $N_Y = 1.532$ ,  $N_Z = 1.536$ ,  $N_Z - N_X = 0.021$ . Again: <sup>85</sup>  $2V = 7^\circ$ ,  $N_X = 1.507$ ,  $N_Y = 1.527$ ,  $N_Z = 1.529$ ,  $N_Z - N_X = 0.022$ .

<sup>82</sup> B. Gossner and I. Koch: *Zeit. Krist.*, LXXX, 455 (1931).

<sup>83</sup> A. Bellanca: *Min. Abst.*, X, 18 (1947).

<sup>84</sup> F. Zambonini: *Comp. Rend.*, CLXXII, 1419 (1921).

<sup>85</sup> M. N. Godlevsky: *Mem. Soc. Russe Mineral.*, LXVIII, 576 (1939).

Color pale yellow, gray, white, rarely red; colorless in section.

**OCCUR.** Glauberite is found in salt deposits with halite, anhydrite, gypsum, etc.

**DIAG.** It differs from anhydrite in having weaker birefringence, smaller optic angle, and inclined extinction; also in having only one good cleavage. It differs from polyhalite in having a much smaller optic angle; also the good cleavage is nearly normal to the acute bisectrix in glauberite and inclined to one optic axis in polyhalite.

**Vanthoffite**  $\text{Na}_6\text{Mg}(\text{SO}_4)_4$  is probably monoclinic; with no cleavage; usually massive.  $H. = 4$ .  $G. = 2.69$ .  $F. = \text{easy}$ . Soluble in water.  $(- )2V = 84^\circ \pm$ ,  $r < v$ .  $N_X = 1.485$ ,  $N_Y = 1.488$ ,  $N_Z = 1.489$ ,  $N_Z - N_X = 0.004$ . Colorless. Found in salt deposits, as at Stassfurt, Prussia.

### (a) WITHOUT ADDITIONAL ANIONS—HYDROUS

**Loewite**  $[\text{Na}_2\text{Mg}(\text{SO}_4)_2 \cdot 2.5\text{H}_2\text{O}]$  is tetragonal with distinct basal cleavage.  $H. = 3.5$ .  $G. = 2.37$ .  $F. = 1.5$ . Soluble in water. Uniaxial negative<sup>86</sup> with  $N_O = 1.490$ ,  $N_E = 1.471$ ,  $N_O - N_E = 0.019$ . Also may be slightly biaxial. Found with anhydrite in salt deposits, as at Stassfurt, Prussia.

**Chile-Loewite**<sup>87</sup>  $[\text{K}_2\text{Na}_4\text{Mg}_2(\text{SO}_4)_5 \cdot 5\text{H}_2\text{O}]$  is hexagonal with  $c/a = 1.19$ . Crystals rhombohedral.  $G. = 2.15$  *ca.* Uniaxial negative with  $N_O = 1.470$ ,  $N_E = 1.434$ ,  $N_O - N_E = 0.036$ .

**Ferrinatrite**  $[\text{Na}_3\text{Fe}(\text{SO}_4)_3 \cdot 3\text{H}_2\text{O}]$  is hexagonal scalenohedral<sup>88</sup> with  $c/a = 0.556$ . Crystals acicular with perfect  $10\bar{1}0$  and distinct  $0001$  cleavages.  $H. = 2.5$ .  $G. = 2.57$ .  $F. = 1.5$ . Soluble in water. Uniaxial positive with  $N_O = 1.559$ ,  $N_E = 1.627$ ,  $N_E - N_O = 0.068$ . Again:<sup>10</sup>  $N_O = 1.557$ ,  $N_E = 1.615$ ,  $N_E - N_O = 0.058$ . Color white or pale green or amethystine. Found with other sulfates, as in Chile.

### SYNGENITE

#### MONOCLINIC PRISMATIC<sup>89</sup>



$$a:b:c = 1.352:1:0.871 \quad \beta = 104^\circ 5'$$

**PHYS. CHAR.** Crystals prismatic, flattened parallel to 100, with perfect 110 and 100 cleavages; twinning on 100.  $H. = 2.5$ .  $G. = 2.58$ .  $F. = 1.5-2$ . Partly soluble in water.

**OPT. PROP.** The optic plane and  $Z$  are normal to 010;  $Y \wedge c = 2^\circ 45'$ .  $(- )2V = 28^\circ 18'$  Na,  $r < v$  strong.  $N_X = 1.501$ ,  $N_Y = 1.517$ ,  $N_Z = 1.518$ ,  $N_Z - N_X = 0.017$ . Also<sup>90</sup>  $X \wedge c = 4^\circ$ ,  $(- )2V = 25^\circ$  *ca.*,  $N_X = 1.500$ ,  $N_Y = 1.515$ ,  $N_Z = 1.520$ ,  $N_Z - N_X = 0.020$ . Colorless.

On heating, syngenite becomes uniaxial for red at  $127^\circ \text{C.}$ , for yellow at  $158^\circ \text{C.}$ , for blue at  $178^\circ \text{C.}$ , the optic plane changing to 010. The dispersion increases until it becomes uniaxial; then it decreases.<sup>91</sup>

**OCCUR.** Syngenite is found in beds with gypsum, anhydrite, etc.

**Koktaite**<sup>92</sup>  $[(\text{NH}_4)_2\text{Ca}(\text{SO}_4)_2 \cdot \text{H}_2\text{O}]$  is monoclinic, like syngenite. Crystals prismatic acicular.  $G. = 2.09$ .  $Y = b$ ,  $Z' \wedge c = 2^\circ$  (on 110).  $(- )2V = 72^\circ$ ,  $N_X$

<sup>86</sup> R. Görges: *Tsch. Min. Pet. Mit.*, XXVIII, 334 (1909).

<sup>87</sup> W. Wetzel: *Chem. Erde*, III, 375 (1927).

<sup>88</sup> S. G. Gordon: *Not. Nat. Acad. Sci. Phila.*, 103, 1942.

<sup>89</sup> A. Laskiewicz: *Min. Abst.*, VI, 414 (1937).

<sup>90</sup> R. D. Terzaghi: *Am. Mineral.*, XVI, 309 (1931).

<sup>91</sup> H. Schreiber: *N. Jahrb. Min.*, Bl. Bd. XXXVII, 247 (1914).

<sup>92</sup> J. Sekanina: *Min. Abst.*, X, 352 (1948).



$= 1.524$ ,  $N_Y = 1.532$ ,  $N_Z = 1.536$ ,  $N_Z - N_X = 0.012$ . Colorless. Found in dumps at a lignite mine.

**Kroehnkite**  $[Na_2Cu(SO_4)_2 \cdot H_2O]$  is monoclinic prismatic<sup>93</sup> with  $a:b:c = 0.459:1:0.436$ ,  $\beta = 108^\circ 30'$ . Crystals prismatic to fibrous with perfect 010 and poor  $\bar{1}01$  cleavages. Twinning on  $\bar{1}01$ .  $H. = 2.5$ .  $G. = 2.90$ .  $F. = 1$ . Soluble in water. The optic plane is 010;  $X \wedge c = -48^\circ$ , larger for red than for blue.  $(- )2V = 79^\circ$ ,  $r < v$  weak.  $N_X = 1.544$ ,  $N_Y = 1.578$ ,  $N_Z = 1.601$ ,  $N_Z - N_X = 0.057$ . Color blue. Found at a copper deposit in Chile.

**Bloedite**  $[Na_2Mg(SO_4)_2 \cdot 4H_2O]$  is monoclinic prismatic<sup>94</sup> with  $a:b:c = 1.349:1:0.675$ ,  $\beta = 100^\circ 48'$ . Space group  $P2_1/a$ ;  $a$  11.04,  $b$  8.15,  $c$  5.49; U.C. 2. Crystals prismatic or 001 tablets with no cleavage.  $H. = 3$ .  $G. = 2.23$ .  $F. = 1.5$ . Soluble in water. The optic plane is 010;  $X \wedge c = 39^\circ 10'$  (469),  $41^\circ 0'$  (598),  $41^\circ 35'$  (644) in the acute angle  $\beta$ .  $(- )2V = 69^\circ 24'$ ,  $r < v$  strong.  $N_X = 1.483$ ,  $N_Y = 1.486$ ,  $N_Z = 1.487$ ,  $N_Z - N_X = 0.004$  (Schaller<sup>95</sup>). Also  $(- )2V = 71^\circ$ ,  $N_X = 1.486$ ,  $N_Y = 1.488$ ,  $N_Z = 1.489$ ,  $N_Z - N_X = 0.003$  (Larsen<sup>3</sup>). Colorless to green or yellow. Found in salt deposits.

**Leonite**  $[K_2Mg(SO_4)_2 \cdot 4H_2O]$  is monoclinic prismatic<sup>96</sup> with  $a:b:c = 1.386:1:1.234$ ,  $\beta = 95^\circ 10'$ . Space group  $C2/m$ . U.C. 4. Crystals tabular with no distinct cleavage. Lamellar twinning often in two sets at about  $60^\circ$ .  $H. = 3$ .  $G. = 2.25$ .  $F. = \text{easy}$ . Soluble in water. The optic plane is 010;  $Z$  nearly normal to 001.  $(- )2V = 86^\circ$ ,  $r < v$ .  $N_X = 1.483$ ,  $N_Y = 1.487$ ,  $N_Z = 1.490$ ,  $N_Z - N_X = 0.007$ . Also  $(+ )2V = \text{nearly } 90^\circ$ ,  $N_X = 1.478$ ,  $N_Y = 1.481$ ,  $N_Z = 1.486$ ,  $N_Z - N_X = 0.008$ . Colorless. Found in salt deposits, as at Leopoldshall, Germany.

**Wattevillite**  $[Na_2Ca(SO_4)_2 \cdot 4H_2O]$  is monoclinic in hair-like forms.  $G. = 1.81$ .  $F. = 1.5-2$ . Soluble in HCl. Extinction<sup>3</sup> of fibers not uniform;  $X$  appears parallel to fibers in some and normal in others, sometimes with a large extinction angle.  $(- )2V = 48^\circ$ ,  $N_X = 1.435$ ,  $N_Y = 1.455$ ,  $N_Z = 1.459$ ,  $N_Z - N_X = 0.024$ . Color white. Luster silky. Found on lignite in Bavaria.

**Picromerite**  $[K_2Mg(SO_4)_2 \cdot 6H_2O]$  is monoclinic prismatic with  $a:b:c = 0.741:1:0.499$ ,  $\beta = 104^\circ 48'$ . Crystals short prismatic with perfect  $20\bar{1}$  cleavage.  $H. = 2.5$ .  $G. = 2.1$ .  $F. = 2$ . Soluble in water. Yields water at low temperature. The optic plane<sup>98</sup> is 010;  $Z \wedge c = +76^\circ 22'$  and  $X \wedge c = -13^\circ 38'$ . See Fig. 105.  $(+ )2V = 48^\circ$ ,  $r > v$  weak.  $N_X = 1.460$ ,  $N_Y = 1.462$ ,  $N_Z = 1.475$ ,  $N_Z - N_X = 0.015$ .  $F - C$  for  $N_Y = 0.0073$ . Colorless. Found at Vesuvius, in salt deposits, and in ores in Chile.<sup>10</sup>

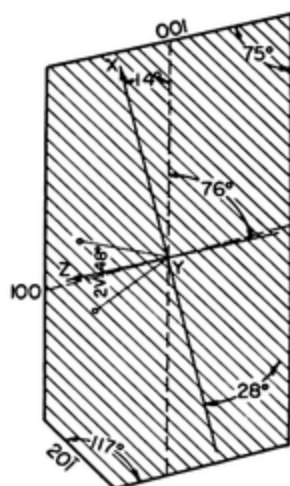


FIG. 105. The optic orientation of picromerite.

<sup>93</sup> C. Palache: *Am. Jour. Sci.*, CCXXXVII, 447 (1939).

<sup>94</sup> C. Lauro: *Per. Mineral. Roma*, XI, 39 (1940).

<sup>95</sup> W. T. Schaller: *Am. Mineral.*, XVII, 530 (1932).

<sup>96</sup> The very similar *manganleonite*  $[K_2Mn(SO_4)_2 \cdot 4H_2O]$  has  $a:b:c = 1.253:1:1.040$ ,  $\beta = 95^\circ$ ;  $G. = 2.31$ .  $H.$  Anspach: *Zeit. Krist.*, CI, 39 (1939).

<sup>97</sup> W. T. Schaller, E. P. Henderson: *U. S. Geol. Surv. Bull.* 833, 46 and 80 (1932).

<sup>98</sup> Optic data partly from artificial crystals. See A. E. H. Tutton: *Jour. Chem. Soc.*, LXIX, 356 (1896), and LXXXVII, 1160 (1905).

**Boussingaultite**  $[(\text{NH}_4)_2\text{Mg}(\text{SO}_4)_2 \cdot 6\text{H}_2\text{O}]$  is monoclinic with  $a:b:c = 0.740:1:0.492$ ,  $\beta = 107^\circ 6'$ . Crystals short prismatic with perfect  $20\bar{1}$  and distinct 010 cleavages.  $H. = 2$ .  $G. = 1.72$ .  $F. = 1$ . Soluble in water. The optic plane<sup>98</sup> is 010;  $Z \wedge c = +85^\circ$ ,  $(+ )2V = 51^\circ$ ,  $r > v$  weak.  $N_X = 1.470$ ,  $N_Y = 1.472$ ,  $N_Z = 1.479$ ,  $N_Z - N_X = 0.009$  (Larsen<sup>99</sup>). Color white. Found about volcanoes and in Tuscan lagoon deposits.

### (b) WITH ADDITIONAL ANIONS—ANHYDROUS

**Phoenicochroite**  $[\text{Pb}_3\text{O}(\text{CrO}_4)_2]$  is orthorhombic with one perfect cleavage. Usually tabular.  $H. = 3-3.5$ .  $G. = 5.75$ .  $F. = \text{easy}$ . Soluble in HCl.  $(+ )2V = \text{medium}$ ,  $r > v$  strong.  $N_X = 2.34$ ,  $N_Y = 2.38$ ,  $N_Z = 2.65$ ,  $N_Z - N_X = 0.31(?)$ . Color cochineal to hyacinth red, altering to lemon yellow. Streak brick red. Found with crocoite in the Urals.

**Lindgrenite**<sup>100</sup>  $[\text{Cu}_3(\text{OH})_2(\text{MoO}_4)_2]$  is monoclinic prismatic with  $a:b:c = 0.399:1:0.384$ ,  $\beta = 98^\circ 23'$ . Space group  $P2_1/m$ ;  $a$  5.60,  $b$  14.03,  $c$  5.39 kX. U.C. 2. Crystals {010} tablets with perfect 010 cleavage.  $H. = 4.5$ .  $G. = 4.26$ . Soluble in HCl. The optic plane and  $Z$  are normal to 010;  $X \wedge c = +7^\circ$ .  $(- )2V = 71^\circ$ ,  $r > v$ .  $N_X = 1.930$ ,  $N_Y = 2.002$ ,  $N_Z = 2.020$ ,  $N_Z - N_X = 0.090$ . Color green; not pleochroic. Found in veinlets in quartz at Chuquicamata, Chile.

### (b) WITH ADDITIONAL ANIONS—HYDROUS

**Sideronatrite**  $[\text{Na}_4\text{Fe}_2(\text{OH})_2(\text{SO}_4)_4 \cdot 6\text{H}_2\text{O}]$  is orthorhombic(?); crystals fibrous with perfect 100 cleavage.  $H. = 2-2.5$ .  $G. = 2.3$ .  $F. = 2$ . Soluble in acid. The optic plane is 010;  $Z = c$ .  $(+ )2V = 58^\circ$ ,  $r > v$  strong.  $N_X = 1.508$ ,  $N_Y = 1.525$ ,  $N_Z = 1.586(-1.595)$ ,  $N_Z - N_X = 0.078$ . Color orange to straw yellow. Pleochroic with  $X = \text{colorless}$ ,  $Y = \text{very pale amber yellow}$ ,  $Z = \text{pale amber yellow}$ . Found in iron deposits in Chile.

**Metasideronatrite**<sup>10</sup>  $[\text{Na}_4\text{Fe}_2(\text{OH})_2(\text{SO}_4)_4 \cdot 3\text{H}_2\text{O}]$  is orthorhombic dipyramidal with  $a:b:c = 0.457:1:0.119$ . Space group  $Pmmm$ . Crystals rare, prismatic. Perfect 100 and 010 and eminent 001 cleavages.  $H. = 2.5$ .  $G. = 2.46$ . Soluble in dilute acids. The optic plane is 010;  $Z = c$ .  $(+ )2V = 60^\circ$ ,  $r > v$  strong.  $N_X = 1.543$ ,  $N_Y = 1.575$ ,  $N_Z = 1.634$ ,  $N_Z - N_X = 0.091$ . Color yellow with  $X = \text{colorless}$ ,  $Y = \text{light yellow}$ ,  $Z = \text{brownish yellow}$ . Found at Chuquicamata, Chile.

**Natrochalcite**<sup>101</sup>  $[\text{NaCu}_2\text{OH}(\text{SO}_4)_2 \cdot \text{H}_2\text{O}]$  is monoclinic prismatic with  $a:b:c = 1.424:1:1.214$ ,  $\beta = 118^\circ 42.5'$ . Space group  $C2/m$ ;  $a$  8.74,  $b$  6.15,  $c$  6.53 Å. U.C. 2. Crystals pyramidal with perfect 001 cleavage.  $H. = 2.5$ .  $G. = 3.48$ .  $F. = \text{easy}$ . Soluble in water. The optic plane is 010;  $Z \wedge c = 12^\circ$ , distinctly less for blue than for red.  $(+ )2V = 37^\circ$ ,  $r < v$  strong.  $N_X = 1.649$ ,  $N_Y = 1.656$ ,  $N_Z = 1.714$ ,  $N_Z - N_X = 0.065$ . Color emerald green. Found in a copper deposit in Chile.

<sup>98</sup> E. S. Larsen and E. V. Shannon: *Am. Mineral.*, V, 127 (1920).

<sup>100</sup> W. H. Barnes: *Am. Mineral.*, XXXII, 684 (1947); XXXIV, 163 (1949).

<sup>101</sup> C. Palache: *Am. Jour. Sci.*, CCXXXVII, 447 (1939).

4. Sulfates with type formula  $\approx A_2BX_4$ 

## (a) WITHOUT ADDITIONAL ANIONS—ANHYDROUS

**APHTHITALITE**<sup>102</sup> HEXAGONAL SCALENOHEDRAL  $c/a = 1.29$   $NaK_3(SO_4)_2$   
 COMP. A double salt—not a crystal solution. The Na:K ratio seems to vary from about 1:4 to about 1:1.

STRUC.<sup>102</sup> Space group  $C\bar{3}m$ ;  $a$  5.65,  $c$  7.29 Å for hexagonal cell. U.C. 1.

PHYS. CHAR. Crystals basal plates, with good prismatic cleavage.  $H. = 3$ .  $G. = 2.70$ .  $F. = 1.5$ . Soluble in water.

OPT. PROP. Uniaxial positive with  $N_O = 1.487$ – $1.491$ ,  $N_E = 1.492$ – $1.499$ ,  $N_E - N_O = 0.005$ – $0.009$  (refrindex and birefringence increasing with increase in tenor of K). Color white.

OCCUR. Found about volcanoes and in some salt deposits.

**THENARDITE**

ORTHORHOMBIC DIPYRAMIDAL

 $Na_2SO_4$  $a:b:c = 0.598:1:1.252$ 

STRUC. Space group<sup>103</sup>  $Fddd$ ;  $a$  5.85,  $b$  12.29,  $c$  9.75 Å, U.C. 8. Whence  $a:b:c = 0.476:1:0.794$ . By interchanging  $b$  and  $c$ , one obtains  $a:b:c = 0.600:1:1.261$ .

PHYS. CHAR. Crystals pyramidal, short prismatic, or basal plates. Distinct basal cleavage.  $H. = 2.7$ .  $G. = 2.68$ .  $F. = 1.5$ – $2$ . Very soluble in water.

OPT. PROP. The optic plane is 001;  $Z = b$  (Spencer<sup>104</sup>).  $(+)2V = 83^\circ$ ,  $r > v$  weak.  $N_X = 1.464$ ,  $N_Y = 1.474$ ,  $N_Z = 1.485$ ,  $N_Z - N_X = 0.021$  (Larsen<sup>3</sup>). Again:  $(+)2V = 83^\circ$ ,  $N_X = 1.4677$ ,  $N_Y = 1.4729$ ,  $N_Z = 1.4812$ ,  $N_Z - N_X = 0.0145$  (Spencer<sup>104</sup>).

INVER. Thenardite inverts at about  $235^\circ$  C. to a hexagonal(?) phase which is uniaxial negative with weak birefringence. Lacroix<sup>105</sup> found this phase at Mont Pelée and called it *metathenardite*.

OCCUR. Found about volcanoes and in salt deposits associated with hanksite, glauberite, ulexite, as in central Asia and at Borax Lake, California.

**Mercallite** ( $HKSO_4$ ) is orthorhombic<sup>106</sup> in tablets.  $G. = 2.31$ . Soluble in water.  $(+)2V = 56^\circ$ ,  $N_X = 1.445$ ,  $N_Y = 1.454$  (calc.),  $N_Z = 1.491$ ,  $N_Z - N_X = 0.046$ . Color sky blue. Found in the crater of Vesuvius.

**Mascagnite**  $[(NH_4)_2SO_4]$  is orthorhombic dipyramidal with  $a:b:c = 0.563:1:0.732$ . Space group  $Pmcn$ ;  $a$  5.97,  $b$  10.60,  $c$  7.76 Å. U.C. 4. Distinct 001 cleavage.  $H. = 2$ .  $G. = 1.77$ ,  $F. = 1$ . Volatile.  $X = c$ ,  $Y = b$ .  $(+)2V = 52^\circ$ ,  $r > v$  very weak.  $N_X = 1.521$ ,  $N_Y = 1.523$ ,  $N_Z = 1.533$ ,  $N_Z - N_X = 0.012$ . Colorless or yellow. Found in guano and about volcanoes.

**Arcanite** ( $K_2SO_4$ ) is orthorhombic dipyramidal with  $a:b:c = 0.573:1:0.742$ . Space group  $Pmcn$ ;  $a$  5.76,  $b$  10.05,  $c$  7.46 Å. U.C. 4. Crystals nearly equant or {010} tablets. May be pseudohexagonal by twinning on 110.  $G. = 2.66$ . Soluble in water.  $X = b$ ,  $Y = a$ .  $(+)2V = 67^\circ$ ,  $r > v$  very weak.  $N_X = 1.4935$ ,  $N_Y = 1.4947$ ,  $N_Z = 1.4973$ ,  $N_Z - N_X = 0.0038$  (artificial). Colorless. Inverts to a negative uniaxial phase at about  $650^\circ$  C.

<sup>102</sup> B. Gossner: *N. Jahrb. Min.*, Bl. Bd. LVIIIA, 89 (1928).

<sup>103</sup> W. H. Zachariasen and G. E. Ziegler: *Zeit. Krist.*, LXXXI (1932).

<sup>104</sup> E. Spencer: *Mineral. Mag.*, XXVII, 29 (1944).

<sup>105</sup> A. Lacroix: *Bull. Soc. Fr. Min.*, XXVIII, 60 (1905).

<sup>106</sup> G. Carobbi: *Min. Abst.*, VI, 148 (1935).

**Taylorite**  $[(\text{NH}_4)_2\text{K}_{10}(\text{SO}_4)_6]$  is concretionary and probably orthorhombic.  $H. = 2$ .  $G. = 1.5(?)$ .  $(-)\text{2V} = \text{sm.}$ ,  $N_X = 1.5007$ ,  $N_Y = 1.5034$ ,  $N_Z = 1.5048$ ,  $N_Z - N_X = 0.004$  (new data). Colorless. Found in guano on the Chincha Islands. Taylorite may be part of an isomorphous series between mascagnite and arcanite.

**Letovicite** <sup>107</sup>  $[(\text{NH}_4)_3\text{H}(\text{SO}_4)_2]$  is monoclinic; basal lamellae with lamellar twinning and indistinct 001 cleavage.  $G. = 1.81$ . Soluble in water.  $Z = b$ ;  $X \wedge c = 17^\circ 30'$ .  $(-)\text{2V} = 52^\circ$ ,  $N_X = 1.501$ ,  $N_Y = 1.516$ ,  $N_Z = 1.526$ ,  $N_Z - N_X = 0.025$  (Rost <sup>108</sup>). Colorless. Found with sulfur in Moravia.

**Misenite** <sup>106</sup>  $(\text{K}_2\text{SO}_4 \cdot 6\text{HKSO}_4)$  is monoclinic prismatic in silky fibers or basal plates; 010 cleavage in traces.  $F. = \text{easy}$ . Soluble in water. The optic plane is normal to 010; extinction is at  $16^\circ$ .  $(+)\text{2V} = 33^\circ$ ,  $N_{Z'} = 1.466$ ,  $N_Z - N_X = \text{weak}$  (Carobbi <sup>106</sup>).  $Z \wedge \text{elongation} = 33^\circ$ ,  $N_X = 1.475$ ,  $N_Y = 1.480$ ,  $N_Z = 1.487$ ,  $N_Z - N_X = 0.012$  (Larsen <sup>3</sup>). Colorless. Found at Cape Misene, Italy.

### (a) WITHOUT ADDITIONAL ANIONS—HYDROUS

**Lecontite**  $(\text{NaNH}_4\text{SO}_4 \cdot 2\text{H}_2\text{O})$  is orthorhombic dipyramidal with  $a:b:c = 0.486:1:0.633$ . Crystals prismatic with 110 cleavage.  $H. = 2.5$ .  $F. = 1$ . Soluble in water. The optic plane is 001;  $X = a$ .  $(-)\text{2E} = 62^\circ 30'$  Li,  $64^\circ 30'$  Na,  $66^\circ 30'$  Tl.  $N_Z = 1.453$ ,  $N_Y = 1.452$ ,  $N_X = 1.440$ ,  $N_Z - N_X = 0.013$ . Colorless. Found in guano in Central America.

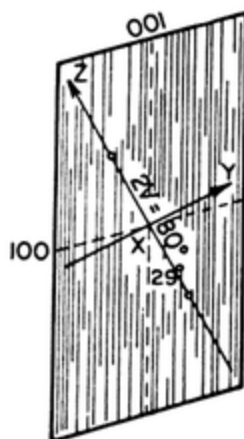


FIG. 106. The optic orientation of mirabilite.

**MIRABILITE** MONOCLINIC PRISMATIC  $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$   
 $a:b:c = 1.116:1:1.238$   $\beta = 107^\circ 45'$

**PHYS. CHAR.** Crystals like pyroxene in habit and angles; in crusts. Perfect 100 cleavage.  $H. = 1.5-2$ .  $G. = 1.46$ .  $F. = 1.5$ . Soluble in water. Effloresces rapidly.

**OPT. PROP.** The optic plane and  $X$  are normal to 010;  $Z \wedge c = -31^\circ$  Li,  $-26.5^\circ$  blue.  $(-)\text{2V} = 80^\circ 26'$ ,  $r > v$  weak, with strong crossed dispersion. See Fig. 106.  $N_X = 1.394$ ,  $N_Y = 1.396$ ,  $N_Z = 1.398$ ,  $N_Z - N_X = 0.004$  (Larsen <sup>3</sup>). Sections normal to  $X$  give abnormal interference colors without extinction; other sections give sharp extinction. Color white.

**OCCUR.** Formed at some hot springs; also in salt-lake deposits; also by the action of volcanic gases on sea water.

**DIAG.** Mirabilite is characterized by its special modes of formation, its crystal form, its efflorescent property, and its cool, bitter taste; also by the extremely low refringence, large extinction angle, and strong dispersion.

### (b) WITH ADDITIONAL ANIONS—ANHYDROUS

**Alunite** <sup>109</sup>  $[\text{KAl}_3(\text{OH})_6(\text{SO}_4)_2]$  is ditrigonal pyramidal with  $c/a = 2.492$ . Space group  $R\bar{3}m$ ;  $a$  6.96,  $c$  17.35 Å. Hexagonal U.C. 3. Crystals rhombohedrons (like cubes), or with base, with distinct basal cleavage.  $H. = 4$ .  $G. = 2.75$ .  $F. = 7$ ,

<sup>107</sup> J. Sekanina: *Zeit. Krist.*, LXXXIII, 117 (1932).

<sup>108</sup> R. Rost: *N. Jahrb. Min.*, I, 360 (1938).

<sup>109</sup> S. B. Hendricks: *Am. Mineral.*, XXII, 773 (1937).

but decrepitate. Insoluble in acid. Uniaxial positive with  $N_O = 1.572$ ,  $N_E = 1.592$ ,  $N_E - N_O = 0.020$ . Again: <sup>110</sup>  $N_O = 1.580$ ,  $N_E = 1.590$ ,  $N_E - N_O = 0.010$ . Basal plates have negative elongation. Colorless or white. Produced by sulfurous vapors affecting acid volcanic rocks, etc.; also by sulfated meteoric waters affecting aluminous rocks. Differs from brucite in occurrence and associated minerals; also has inferior cleavage and brittle laminae. Distinguished from sericite by the sign of elongation and uniaxial character.

**Natroalunite**  $[NaAl_3(OH)_6(SO_4)_2]$  is ditrigonal pyramidal with distinct basal cleavage.  $H. = 4$ .  $G. = 2.6$ . Uniaxial positive with  $N_O = 1.568$ ,  $N_E - N_O = 0.01$ . Rare. A series between alunite and natroalunite is suggested by a sample from Texas <sup>110</sup> with about 50% alunite and 35% natroalunite having  $N = 1.58$  and  $N_E - N_O = 0.005$ ; a sample from Death Valley, California, <sup>110</sup> with about 50% natroalunite having  $N = 1.585$  and  $N_E - N_O = 0.01$ ; and a sample from Hawaii <sup>111</sup> with about 54% natroalunite, having  $N_O = 1.570$  and  $N_E - N_O = 0.020+$ .

**Jarosite** <sup>109</sup>  $[KFe_3(OH)_6(SO_4)_2]$  is ditrigonal pyramidal with  $c/a = 2.361$ . Space group  $R\bar{3}m$ ;  $a$  7.20,  $c$  17.00 Å. Hexagonal U.C. 3. Crystals rhombohedrons, like cubes, or with base; also fibrous or granular massive. Distinct basal cleavage.  $H. = 3$ .  $G. = 3.26$ .  $F. = 4.5$ . Soluble in HCl. Uniaxial negative with  $N_O = 1.820$ ,  $N_E = 1.715$ ,  $N_O - N_E = 0.105$ . Color yellow; pleochroic with  $O =$  golden yellow or straw yellow,  $E =$  very pale golden yellow or colorless. May invert to an orthorhombic phase in which a basal section shows twinning in six segments, each one having the optic plane parallel with the edge and  $(- )2V =$  very small,  $N_X = 1.715$ ,  $N_Y = 1.817$ ,  $N_Z = 1.820$ ,  $N_Z - N_X = 0.105$ . Artificial jarosites easily produced.<sup>112</sup> Tarnishes easily and changes slowly to limonite. Found about mines, often associated with limonite. Differs from other basic iron sulfates in containing potash, and from metavoltine in its complete insolubility in water.

**Ammoniojarosite** <sup>109</sup>  $[NH_4Fe_3(OH)_6(SO_4)_2]$  is ditrigonal pyramidal with  $c/a = 2.36$ . Space group  $R\bar{3}m$ ;  $a$  7.20,  $c$  17.00 Å. Hexagonal U.C. 3. Crystals six-sided plates.  $G. = 3.09$ . Soluble in HCl. Uniaxial negative with  $N_O = 1.800$ ,  $N_E = 1.750$ ,  $N_O - N_E = 0.050$ . Again: <sup>113</sup>  $N_O = 1.830$ ,  $N_E = 1.745$ ,  $N_O - N_E = 0.085$ . Color yellow. Found in southern Utah.

**Natrojarosite** <sup>109</sup>  $[NaFe_3(OH)_6(SO_4)_2]$  is ditrigonal pyramidal with  $c/a = 2.27$ . Space group  $R\bar{3}m$ ;  $a$  7.18,  $c$  16.30 Å. Hexagonal U.C. 3.  $H. = 3$ .  $G. = 3.2$ .  $F. = 4.5$ . Soluble in HCl. Uniaxial negative with  $N_O = 1.832$ ,  $N_E = 1.750$ ,  $N_O - N_E = 0.082$ . A sample with more  $H_2O$   $[NaFe_3(OH)_6(SO_4)_2 \cdot H_2O]$  has  $G. = 3.06$ ,  $N_O = 1.78$ ,  $N_E = 1.69$ ,  $N_O - N_E = 0.09$  (Bøgvad <sup>114</sup>). Color yellow or brown; pleochroic with  $O =$  pale yellowish,  $E =$  colorless. Found in Nevada, New Mexico, South Dakota.

**Argentojarosite** <sup>109</sup>  $[AgFe_3(OH)_6(SO_4)_2]$  is ditrigonal pyramidal with  $c/a = 2.27$ . Space group  $R\bar{3}m$ ;  $a$  7.22,  $c$  16.40 Å. Hexagonal U.C. 3. Distinct basal cleavage.  $G. = 3.80$ . Uniaxial negative <sup>115</sup> with  $N_O = 1.905$ ,  $N_E = 1.785$ ,  $N_O - N_E = 0.120$ . Color yellow to brown with  $O > E$ . Found in the oxide zone of a silver vein at Dividend, Utah.

<sup>110</sup> E. T. Wherry: *Proc. U. S. Nat. Mus.*, LI, 81 (1916).

<sup>111</sup> J. D. Loudermilk: *Am. Mineral.*, XX, 57 (1935).

<sup>112</sup> J. G. Fairchild: *Am. Mineral.*, XVIII, 543 (1933).

<sup>113</sup> R. Jirkovsky: *Min. Abst.*, V, 188 (1932).

<sup>114</sup> R. Bøgvad: *Medd. Dansk. Geol. For.*, X, 108 (1942).

<sup>115</sup> Harry Berman: personal communication, July 17, 1931.



**Plumbojarosite** <sup>109</sup>  $[\text{Pb}\{\text{Fe}_3(\text{OH})_6(\text{SO}_4)_2\}_2]$  is ditrigonal pyramidal with  $c/a = 4.67$ . Space group  $R3m$ ;  $a$  7.20,  $c$  33.60 Å. Hexagonal U.C. 6. Crystals six-sided basal plates. Rhombohedral cleavage.  $G. = 3.67$ . Uniaxial negative with  $N_O = 1.875$ ,  $N_E = 1.785$ ,  $N_O - N_E = 0.090$ . Also <sup>116</sup>  $N_O = 1.9$ ,  $N_E = 1.722$ ,  $N_O - N_E = 0.178$ . Color brown to golden yellow with  $O = \text{dark brownish red}$ ,  $E = \text{pale golden yellow}$ . Also biaxial with  $(- )2V = \text{small}$ ;  $X$  normal to plates which are divided into six segments. Found in New Mexico.

**Carphosiderite** <sup>109</sup>  $[\text{HFe}_3(\text{OH})_6(\text{SO}_4)_2]$  is hexagonal, closely related to jarosite in structure. Crystals platy; distinct basal cleavage.  $H. = 4-4.5$ .  $G. = 2.5-2.7$ . Soluble in  $\text{HCl}$ . Uniaxial negative with  $N_O = 1.82$ ,  $N_E = 1.73$ ,  $N_O - N_E = 0.09$  (Larsen <sup>3</sup>). Color yellow. Found in Greenland and France.

**Vegasite**  $[\text{PbFe}_6(\text{OH})_{14}(\text{SO}_4)_3]$  is hexagonal, much like plumbojarosite. Uniaxial positive with  $N_O = 1.755$ ,  $N_E = 1.82$ ,  $N_E - N_O = 0.065$ . Color yellow, with  $O = \text{pale yellow}$ ,  $E = \text{brownish yellow}$ . Found in ore deposits.

**Koechlinite**  $[(\text{BiO})_2\text{MoO}_4]$  is orthorhombic with  $a:b:c = 0.977:1:1.003$ . Crystals nearly square  $\{100\}$  tablets with diagonal striations parallel to  $c$ . Perfect 100 cleavage. Twinning on 011. Soluble in  $\text{HCl}$ . The optic plane is 001;  $Z = a$ .  $(- )2V = \text{very large}$  (perhaps  $+$ ),  $N_Y = 2.55$  Li,  $N_Z - N_X = 0.1$  (estimate). Color greenish yellow, turning brown when heated, and yellow again on cooling. Weakly pleochroic in thick plates. Found in an ore deposit in Schneeberg, Saxony.

**Dolerophanite**  $(\text{Cu}_2\text{OSO}_4)$  is monoclinic prismatic <sup>117</sup> with  $a:b:c = 1.484:1:1.209$ ,  $\beta = 122^\circ 18.5'$ . Space group  $C2/m$ ;  $a$  9.39,  $b$  6.30,  $c$  7.62 Å. U.C. 4. Crystals columnar along  $b$  with  $\{001\}$ ,  $\{100\}$ ,  $\{\bar{2}01\}$ ,  $\{010\}$ , etc. Perfect basal cleavage.  $G. = 4.17$ . Fusible. Soluble in  $\text{HNO}_3$ . The optic plane is 010;  $Z \wedge c = +10^\circ$ .  $(+ )2V = 85^\circ$ ,  $r > v$  very strong.  $N_X = 1.715$ ,  $N_Y = 1.820$ ,  $N_Z = 1.880$ ,  $N_Z - N_X = 0.165$ . Color brown with  $X = \text{deep brown}$ ,  $Y = \text{brownish yellow}$ ,  $Z = \text{lemon yellow}$ . Found at Vesuvius.

**Linarite** <sup>118</sup>  $[\text{PbCu}(\text{OH})_2\text{SO}_4]$  is monoclinic prismatic with  $a:b:c = 1.716:1:0.830$ ,  $\beta = 102^\circ 37'$ . Crystals elongated along  $b$  or thick basal tablets with perfect 100 and distinct 001 cleavages.  $H. = 2.5$ .  $G. = 5.4$ .  $F. = 1.5$ . Partly soluble in  $\text{HNO}_3$ . The optic plane is normal to 010;  $X \wedge c = +24^\circ$  ( $18^\circ 42'$  Fenoglio <sup>118</sup>); the acute bisectrix is nearly normal to  $\bar{1}01$ , a common large face.  $(- )2V = 80^\circ$ ,  $r < v$  marked.  $N_X = 1.809$ ,  $N_Y = 1.838$ ,  $N_Z = 1.859$ ,  $N_Z - N_X = 0.050$ . Color deep azure blue like azurite; pleochroic with  $X = \text{pale blue}$ ,  $Y = \text{clear blue}$ ,  $Z = \text{Prussian blue}$ . Found in the oxide zone of lead-copper veins with cerussite, caledonite, etc., as in Inyo County, California. Linarite differs from azurite in optic sign, and from caledonite in giving (an uncentered) interference figure from a cleavage fragment.

**Montanite**  $[\text{Bi}_2(\text{OH})_4\text{TeO}_4]$  is monoclinic(?); crystals fibrous; soft and earthy masses.  $G. = 3.79$ .  $F. = 1.5$ . Soluble in  $\text{HCl}$ . Fibers tend to lie on a face nearly normal to  $X$ .  $(- )2V = \text{small}$ ,  $r < v$  extremely strong.  $N = 2.09 \pm$ ,  $N_Z - N_X = 0.01 \pm$ . Color yellowish white; very abnormal interference colors. Found as an alteration product of tetradyte, as at Highland, Montana.

**Lanarkite**  $(\text{Pb}_2\text{OSO}_4)$  is monoclinic prismatic <sup>119</sup> with  $a:b:c = 2.415:1:1.242$ ,  $\beta = 115^\circ 48'$ . Space group  $C2/m$ ;  $a$  13.73,  $b$  5.68,  $c$  7.07 Å; U.C. 4. Crystals  $\{\bar{2}01\}$  tablets or elongated along  $b$ . Perfect  $\bar{2}01$  cleavage.  $H. = 2-2.5$ .  $G. = 6.92$ .  $F. =$

<sup>116</sup> G. C. Ladame: *Min. Abst.*, VIII, 176 (1941); *Schw. Min. Pet. Mit.*, XVIII, 404 (1938).

<sup>117</sup> W. E. Richmond and C. W. Wolfe: *Am. Mineral.*, XXV, 606 (1940).

<sup>118</sup> M. Fenoglio: *Per. Mineral. Roma*, III, 1 (1932).

<sup>119</sup> W. E. Richmond and C. W. Wolfe: *Am. Mineral.*, XXIII, 799 (1938).



977° C. Partly soluble in  $HNO_3$ . The optic plane is 010;  $Z \wedge c = 30^\circ$ ; acute bisectrix visible from cleavage plates.  $(- )2V = 60^\circ$ ,  $N_X = 1.928$ ,  $N_Y = 2.007$ ,  $N_Z = 2.036$ ,  $N_Z - N_X = 0.108$ . White. Alters easily to anglesite, cerussite, or leadhillite. Found in lead ores, as at Leadhills, Scotland. Differs from anglesite and leadhillite in the optic properties of cleavage fragments.

**Cuprotungstite**  $[Cu_2(OH)_2WO_4]$  is cryptocrystalline, fibrous, with one distinct cleavage.  $H. = 4.5$ .  $G. = 3.95$ .  $F. = 3?$ . Decomposed by  $HCl$ .  $N = 2.15 \pm$ ,  $N_Z - N_X = \text{strong}$ . Color green. Found in copper ores with scheelite, as at La Paz, Lower California.

### (b) WITH ADDITIONAL ANIONS—HYDROUS

**Ungemachite** <sup>120</sup>  $[Na_3K_3Fe'''(OH)_2(SO_4)_6 \cdot 10H_2O]$  is rhombohedral with  $c/a = 2.297$ . Space group  $R\bar{3}$ ;  $a$  10.84.  $c$  24.82 Å. U.C. 1. Crystals thick basal plates with perfect 0001 cleavage.  $H. = 2.5$ .  $G. = 2.29$ . Uniaxial negative with  $N_O = 1.502$ ,  $N_E = 1.449$ ,  $N_O - N_E = 0.053$ . Found in Chile.

**Loewigite**  $[KAl_3(OH)_6(SO_4)_2 \cdot 3H_2O]$  is like alunite, but contains more water. Earthy.  $H. = 3-4$ .  $G. = 2.58$ . Partly soluble in  $HCl$ . Optic sign unknown.  $N = 1.575$ ,  $N_Z - N_X = 0.01$ . Found in lumps in coal.

**Beaverite** <sup>121</sup>  $[CuPb(Fe,Al)_2(OH)_6(SO_4)_2 \cdot H_2O?]$  is hexagonal; crystals basal plates.  $G. = 4.36$ . Soluble in  $HCl$ . Uniaxial negative with  $N_O = 1.83-1.87$ ,  $N_O - N_E = 0.04 \text{ ca.}$  Color brown to yellow. An alteration product in ore deposits in Beaver County, Utah.

**Aluminite**  $[Al_2(OH)_4SO_4 \cdot 7H_2O]$  is orthorhombic(?) in earthy fibrous masses.  $H. = 1-2$ .  $G. = 1.66$ .  $F. = 7$ . Soluble in acid.  $X$  is parallel to the elongation and  $Z$  is normal to a face of the zone of elongation.  $(+)2V = \text{large}$ .  $N_X = 1.459$ ,  $N_Y = 1.464$ ,  $N_Z = 1.470$ ,  $N_Z - N_X = 0.011$  (Larsen<sup>3</sup>). Color white. Found in clay, as at Auteuil, France. By dehydration, changes to a monoclinic phase with large positive optic angle and a large extinction angle. An optic axis is nearly normal to a prism face.  $N_Y = 1.500$ ,  $N_Z - N_X = 0.01$  (Larsen<sup>3</sup>).

**Herrengrundite** <sup>122</sup>  $[CaCu_4(OH)_6(SO_4)_2 \cdot 3H_2O?]$  is monoclinic prismatic with  $a:b:c = 1.816:1:2.800$ ,  $\beta = 91^\circ 10'$ . Crystals six-sided  $\{001\}$  plates with perfect 001 and distinct 110 cleavages. Twinning on 001.  $H. = 2.5$ .  $G. = 3.13$ .  $F. = 3.5$ . Soluble in  $HCl$ . Optic plane and  $Z$  normal to 010;  $X$  near  $c$ .  $(-)2V = 39^\circ$ ,  $r < v$  marked.  $N_X = 1.585$ ,  $N_Y = 1.649$ ,  $N_Z = 1.660$ ,  $N_Z - N_X = 0.075$ . Color emerald to bluish green; pleochroic with  $X = \text{very pale green}$ ,  $Y = \text{Venice green}$ ,  $Z = \text{turquoise green}$  and  $X < Y < Z$ . Found in quartz conglomerate in Hungary.

**Kainite**  $(KMgClSO_4 \cdot 3H_2O)$  is monoclinic prismatic with  $a:b:c = 1.219:1:0.586$ ,  $\beta = 94^\circ 55'$ . Crystals basal tablets or pyramidal. Distinct 100 and 110 cleavages. Prismatic cleavage angle is  $79^\circ$ .  $H. = 3$ .  $G. = 2.13$ .  $F. = 1.5-2$ . Soluble in water. The optic plane is 010;  $X \wedge c = +8^\circ$ .  $(-)2V = 85^\circ$ ,  $r > v$  weak, with distinct inclined dispersion.  $N_X = 1.494$ ,  $N_Y = 1.505$ ,  $N_Z = 1.516$ ,  $N_Z - N_X = 0.022$ . Colorless or stained red. Colorless in section. Found with picromerite, halite, sylvite, etc., in salt deposits.

<sup>120</sup> M. A. Peacock and M. C. Bandy: *Am. Mineral.*, XXIII, 314 (1938).

<sup>121</sup> B. S. Butler and W. T. Schaller: *Am. Jour. Sci.*, CLXXXII, 418 (1911).

<sup>122</sup> F. V. Churkhrov and V. M. Senderova: *Min. Abst.*, VII, 558 (1940).

5. Sulfates with type formula  $\approx A_3BX_4$ 

## (a) WITH ADDITIONAL ANIONS—ANHYDROUS

**Sulfohalite** <sup>123</sup>  $[Na_6ClF(SO_4)_2]$  is isometric with  $a$  10.08 Å. Space group  $Fm\bar{3}m$  or  $Fm\bar{3}$ . U.C. 4. Crystals octahedral or dodecahedral, with no cleavage.  $H.$  = 3.5.  $G.$  = 2.43–2.49.  $F.$  = 1. Soluble in  $H_2O$ . Isotropic with  $N$  = 1.454. Colorless. Found at Borax Lake, California.

**Schairerite** <sup>124</sup>  $[Na_3(F,Cl)SO_4]$  is hexagonal with  $c/a$  = 1.77; crystals steep rhombohedrons with no cleavage.  $H.$  = 3.5.  $G.$  = 2.61.  $F.$  = easy. Slowly soluble in  $H_2O$ . Uniaxial positive with  $N_O$  = 1.440,  $N_E$  = 1.445,  $N_E - N_O$  = 0.005. Colorless. Found in a salt deposit at Searles Lake, California.

**Antlerite**  $[Cu_3(OH)_4SO_4]$  is orthorhombic dipyramidal <sup>125</sup> with  $a:b:c$  = 0.687:1:0.503. Space group <sup>126</sup>  $Pnam$ ;  $a$  8.22,  $b$  11.97,  $c$  6.02 Å. U.C. 4. Crystals prismatic with perfect 010 cleavage.  $H.$  = 3.  $G.$  = 3.88. The optic plane is 100;  $X = b$ . (+)2V = 53°,  $N_X$  = 1.726,  $N_Y$  = 1.738,  $N_Z$  = 1.789,  $N_Z - N_X$  = 0.063. Color light green; strongly pleochroic with  $X$  = pale yellowish green,  $Y = Z$  = viridine green, and  $Y > Z > X$ . Found in copper-ore deposits, notably in Chile.

**Caracolite**  $(Na_2PbOHClSO_4?)$  is orthorhombic with  $a:b:c$  = 0.584:1:0.422. Crystals pseudohexagonal pyramids twinned on 110. No cleavage.  $H.$  = 4.5.  $F.$  = 1.5–2. Partly soluble in water. (–)2V = very large,  $r > v$  distinct.  $N_X$  = 1.743,  $N_Y$  = 1.754,  $N_Z$  = 1.764,  $N_Z - N_X$  = 0.021. Colorless. Found in ore deposits, as at Atacama, Chile.

## (b) WITH ADDITIONAL ANIONS—HYDROUS

**Zincaluminite**  $[Zn_6Al_6(OH)_{22}(SO_4)_4 \cdot 7H_2O]$  is hexagonal; platy.  $H.$  = 2.5–3.  $G.$  = 2.26.  $F.$  = 7. Soluble in  $HNO_3$ . Uniaxial negative with  $N_O$  = 1.534,  $N_E$  = 1.514,  $N_O - N_E$  = 0.020. Color white. Found at Laurium, Greece.

**Trudellite** <sup>127</sup>  $[Al_{10}Cl_{12}(OH)_{12}(SO_4)_3 \cdot 30H_2O?]$  is hexagonal with poor rhombohedral cleavage.  $H.$  = 2.5.  $G.$  = 1.93. Very deliquescent. Uniaxial negative with  $N_O$  = 1.560,  $N_E$  = 1.495,  $N_O - N_E$  = 0.065. Color yellow. Found in Chile.

**Ettringite** <sup>128</sup>  $[Ca_6Al_2(OH)_{12}(SO_4)_3 \cdot 27H_2O?]$  is (probably) dihexagonal dipyramidal with  $c/a$  = 1.908. Space group  $C6/mmc(?)$ ;  $a$  11.24,  $c$  21.45 Å. U.C. 2. Crystals acicular, with perfect prismatic cleavage.  $H.$  = 2–2.5.  $G.$  = 1.79. Soluble in  $HCl$ . Uniaxial negative with <sup>128</sup>  $N_O$  = 1.4655,  $N_E$  = 1.4618,  $N_O - N_E$  = 0.0037. Color white. Found in cavities in limestone, in lava, and in a contact zone in County Antrim.

<sup>123</sup> A. Pabst: *Zeit. Krist.*, LXXXIX, 514 (1934); W. F. Foshag: *Am. Mineral.*, XVIII, 431 (1933); T. Watanabe: *Min. Abst.*, VI, 182 (1935).

<sup>124</sup> W. F. Foshag: *Am. Mineral.*, XVI, 133 (1931).

<sup>125</sup> C. Palache: *Am. Mineral.*, XXIV, 293 (1939).

<sup>126</sup> W. E. Richmond: *Am. Mineral.*, XXIV, 300 (1939).

<sup>127</sup> S. G. Gordon: *Proc. Phila. Acad. Sci.*, LXXVII, 317 (1925).

<sup>128</sup> F. A. Bannister: *Mineral. Mag.*, XXIV, 324 (1936).

6. Sulfates with type formula  $A_mBX_4$  with  $m = 4$  or more

## BROCHANTITE

MONOCLINIC PRISMATIC <sup>129</sup>

$$a:b:c = 1.328:1:0.614 \quad \beta = 103^\circ 21'$$

STRUC. Space group  $P2/a$ ;  $a$  13.05,  $b$  9.83,  $c$  5.85 Å. U.C. 4.

PHYS. CHAR. Crystals often prismatic, pseudo-orthorhombic due to twinning on 100; vertically striated. Perfect 100 cleavage.  $H. = 4$ .  $G. = 3.97$ .  $F. = 3.5$ . Soluble in  $HNO_3$ .

OPT. PROP. The optic plane is 010;  $Z \wedge c = 1/3^\circ \pm$ ;  $X \wedge a = 13^\circ \pm$ .  $(- )2V = 77^\circ$ ,  $r < v$  distinct.  $N_X = 1.728$ ,  $N_Y = 1.771$ ,  $N_Z = 1.800$ ,  $N_Z - N_X = 0.072$ . Color emerald green; weakly pleochroic in green with maximum absorption parallel to  $Z$ .

OCCUR. Found in the oxide zone of copper deposits, as in the Tintic district, Utah.

DIAG. Cleavage parallel to the usual elongation which has positive sign; cleavage normal to acute bisectrix  $X$ .

**Connellite**  $[Cu_{19}(OH)_{32}Cl_4SO_4 \cdot 3H_2O?]$  is dihexagonal dipyramidal with  $c/a = 1.185$ . Crystals acicular.  $H. = 3$ .  $G. = 3.38$ .  $F. = 2$ . Soluble in  $HCl$ . Uniaxial positive with  $N_O = 1.724$ ,  $N_E = 1.746$ ,  $N_E - N_O = 0.022$  (Merwin <sup>130</sup>);  $N_O = 1.735$ ,  $N_E = 1.758$ ,  $N_E - N_O = 0.023$  (Pelloux <sup>131</sup>);  $N_O = 1.730$ ,  $N_E = 1.754$ ,  $N_E - N_O = 0.024$  (Ford <sup>132</sup>). Color blue or greenish blue with very weak pleochroism. Found in copper deposits, in Cornwall, etc.

**Spangolite**  $(Cu_6Al(OH)_{12}ClSO_4 \cdot 3H_2O)$  is ditrigonal pyramidal <sup>133</sup> with  $c/a = 1.739$ . Space group  $C3c$ ,  $a$  8.245,  $c$  14.34 Å. U.C. 2. Crystals basal tablets to short prismatic, horizontally striated. Perfect basal cleavage.  $H. = 2-3$ .  $G. = 3.14$ .  $F. = 3$ . Soluble in dilute acids. Uniaxial negative with  $N_O = 1.694$  (green),  $N_E = 1.641$ ,  $N_O - N_E = 0.053$ . Again: <sup>133</sup>  $N_O = 1.680-1.687$ . Color dark green with  $O$  = green,  $E$  = bluish green. Found with cuprite and azurite at Tombstone, Arizona.

**Langite**  $[Cu_4(OH)_6SO_4 \cdot H_2O]$  is orthorhombic dipyramidal with  $a:b:c = 0.535:1:0.635$ . Crystals {001} laths elongated along  $a$ ; also fibrous; twinning on 110. Perfect 001 and distinct 010 cleavages.  $H. = 2.5-3$ .  $G. = 3.49$ .  $F. = 3.5$ . Soluble in  $HCl$ . The optic plane is 010;  $X = c$ .  $(- )2E = 66^\circ-104^\circ$ ,  $N_X = 1.654$ ,  $N_Y = 1.713$ ,  $N_Z = 1.722$ ,  $N_Z - N_X = 0.068$  (Meixner <sup>134</sup>). Color blue to greenish blue with  $X$  = bluish green,  $Y$  = yellowish green,  $Z$  = deep bluish green. Heating changes the color to bright green with loss of 1  $H_2O$ , then olive green, and finally black. Found in slaty schists in Cornwall.

**Glockerite**  $[Fe_4(OH)_{10}SO_4 \cdot H_2O?]$  is found in soft fibrous crusts of a brown, yellow, or green, to black color with  $N_X = 1.76$  and  $N_Z = 1.81$ . May be red in section. Sign unknown. An alteration product of pyrite or marcasite.

**Felsöbányite**  $[Al_4(OH)_{10}SO_4 \cdot 5H_2O?]$  is orthorhombic in six-sided to lath-shaped basal scales with perfect 001 cleavage.  $H. = 1.5$ .  $G. = 2.33$ .  $F. = 7$ . Soluble in

<sup>129</sup> C. Palache: *Am. Mineral.*, XXIV, 463 (1939).

<sup>130</sup> C. Palache and H. E. Merwin: *Am. Jour. Sci.*, CLXXVIII, 537 (1909).

<sup>131</sup> A. Pelloux: *Zeit. Krist.*, LV, 313 (1920).

<sup>132</sup> W. E. Ford and W. M. Bradley: *Am. Jour. Sci.*, CLXXXIX, 670 (1915).

<sup>133</sup> C. Frondel: *Am. Mineral.*, XXXIV, 181 (1949).

<sup>134</sup> H. Meixner: *Min. Abst.*, VIII, 381 (1943). Meixner rejects the old data:  $(- )2V = 81^\circ$ ,  $N_X = 1.708$ ,  $N_Y = 1.760$ ,  $N_Z = 1.798$ ,  $N_Z - N_X = 0.090$ .

acid.  $Z = c$ .  $X$  parallel to elongation.  $(+ )2V = 48^\circ$ ,  $r > v$  distinct,  $N_X = 1.516$ ,  $N_Y = 1.518$ ,  $N_Z = 1.533$ ,  $N_Z - N_X = 0.017$  (Larsen<sup>3</sup>). Color white. Found in Hungary.

**Paraluminite**  $[Al_4(OH)_{10}SO_4 \cdot 10H_2O?]$  is similar, in fibrous masses. Soft.  $X$  parallel to elongation.  $(- )2V =$  small to  $0^\circ$ ,  $N_X = 1.462$ ,  $N_Y = 1.470$ ,  $N_Z = 1.471$ ,  $N_Z - N_X = 0.009$  (Larsen<sup>3</sup>). Color white, chalky. Found in clay beds, as at Huelgoat, Brittany.

**Kyanotrichite**  $[Cu_4Al_2(OH)_{12}SO_4 \cdot 2H_2O]$ , or *lettsonite*, is orthorhombic; crystals lath-shaped in velvety druses.  $G. = 2.74 \pm$ .  $F. = 3$ . Soluble in water. Optic orientation unknown.  $(+ )2V = 84^\circ$  calc.,  $N_X = 1.588$ ,  $N_Y = 1.617$ ,  $N_Z = 1.655$ ,  $N_Z - N_X = 0.067$ . Color bright blue with  $X =$  nearly colorless,  $Y =$  pale blue,  $Z =$  bright blue (Larsen<sup>135</sup>);  $X =$  pale blue,  $Y =$  nearly colorless,  $Z =$  dark azure blue (Lacroix). Found at copper mines in Utah, etc.

**Torreyite**<sup>136</sup>  $[(Mg,Mn,Zn)_7(OH)_{12}SO_4 \cdot 4H_2O]$  is monoclinic. Good 010 cleavage. Common twinning.  $H. = 3$ .  $G. = 2.67$ .  $(- )2V = 40^\circ$  ca.  $N_X = 1.570$ ,  $N_Y = 1.584$ ,  $N_Z = 1.585$ ,  $N_Z - N_X = 0.015$ . Color in mass bluish white. Found at Franklin, New Jersey.

**Glaucocerinite**<sup>137</sup>  $[Zn_{13}Cu_7Al_8(OH)_{60}(SO_4)_2 \cdot 4H_2O?]$  forms fibrous spherulitic masses. Soft.  $G. = 2.75$ . Soluble in HCl.  $Z$  parallel to elongation. Perhaps uniaxial.  $N_Z = 1.542$ ,  $N_Z - N_X =$  strong. Color blue to white. Found with smithsonite and adamite at Laurium, Greece.

**Mooreite**<sup>138</sup>  $[(Mg,Mn,Zn)_8(OH)_{14}SO_4 \cdot 4H_2O]$  is monoclinic with  $a:b:c = 0.552:1:0.964$ ,  $\beta = 122^\circ 23'$ . Space group<sup>139</sup>  $P2_1/m$ ;  $a$  11.18,  $b$  20.25,  $c$  19.52 Å. Crystals {010} plates with perfect 010 cleavage.  $H. = 3$ .  $G. = 2.47$ .  $X = b$ ,  $Z \wedge c = 44^\circ$ . With  $Mg:Mn:Zn =$  about  $4:1:2$ ,  $(- )2V = 50^\circ \pm$ ,  $r > v$ ,  $N_X = 1.533$ ,  $N_Y = 1.545$ ,  $N_Z = 1.547$ ,  $N_Z - N_X = 0.014$ . Colorless. Found at Franklin, New Jersey.

**Creedite**<sup>140</sup>  $[Ca_3Al_2F_4(OH)_6SO_4 \cdot 2H_2O]$  is monoclinic with  $a:b:c = 1.62:1:1.16$ ,  $\beta = 94^\circ 30'$ . Crystals prismatic with perfect 110 cleavage; twinning on 100.  $H. = 4$ .  $G. = 2.72$ .  $F. =$  difficult, with intumescence. Soluble in acid. The optic plane is 010;  $Z \wedge c = 42^\circ$ .  $(- )2V = 64^\circ$ ,  $r > v$  weak.  $N_X = 1.461$ ,  $N_Y = 1.478$ ,  $N_Z = 1.485$ ,  $N_Z - N_X = 0.024$ . Colorless or purple. Found with barite in a fluorite mine in Colorado.

**Chalcoalumite**  $[CuAl_4(OH)_{12}SO_4 \cdot 3H_2O]$  is probably triclinic, in thin crusts with several perfect cleavages yielding lath-shaped forms (in powder) terminated by a face at  $60^\circ$  to the length. Twinning plane parallel to the length of the laths and nearly normal to the flat face.  $H. = 2.5$ .  $G. = 2.29$ . Soluble in HCl.  $Z$  makes large angles with normals to the flat face and the edge face of the laths, whose long faces have negative elongation, though matted fibers may give apparent positive elongation. Strong dispersion, giving abnormal blue interference colors.  $(+ )2V =$  large,  $r > v$  strong.  $N_X = 1.523$ ,  $N_Y = 1.525$ ,  $N_Z = 1.532$ ,  $N_Z - N_X = 0.009$ . Color blue-green. Found on copper ores of Bisbee, Arizona.

<sup>135</sup> C. Palache and H. E. Vassar: *Am. Mineral.*, XI, 213 (1926).

<sup>136</sup> J. Prewitt-Hopkins: *Am. Mineral.*, XXXIV, 589 (1949).

<sup>137</sup> E. Dittler and R. Koechlin: *Cent. Min.*, 1932A, 13.

<sup>138</sup> L. H. Bauer and H. Berman: *Am. Mineral.*, XIV, 165 (1929).

<sup>139</sup> J. Prewitt-Hopkins: *Am. Mineral.*, XXXIV, 589 (1949).

<sup>140</sup> E. S. Larsen and R. C. Wells: *Proc. Nat. Acad. Sci.*, II, 360 (1916); W. F. Foshag: *Am. Mineral.*, XVII, 75 (1932).

## 7. Sulfates with type formula $A_2B_2X_7$

**Lopezite** <sup>141</sup> ( $K_2Cr_2O_7$ ) is triclinic pinacoidal with  $a:b:c = 0.558:1:0.551$ ,  $\alpha = 82^\circ 0'$ ,  $\beta = 90^\circ 51'$ ,  $\gamma = 83^\circ 47'$ , as measured on artificial crystals, which have perfect 010 and good 100 and 001 cleavages. Crystals prismatic, or thick {010} tablets. Twinning on 010, and others.  $G. = 2.69$ . Soluble in water. The optic plane is nearly normal to 001 between 100 and  $0\bar{1}0$ . X makes angles of  $86^\circ 27'$ ,  $68^\circ 6'$ , and  $13^\circ 43'$  with normals to 100,  $0\bar{1}0$ , and 001; Z makes angles of  $77^\circ 5'$ ,  $23^\circ 5'$ , and  $76^\circ 21'$  with normals to 100,  $0\bar{1}0$  and  $00\bar{1}$ .  $(+ )2V = 50^\circ$ ,  $r > v$  medium.  $N_X = 1.714$ ,  $N_Y = 1.732$ ,  $N_Z = 1.805$ ,  $N_Z - N_X = 0.091$  (natural crystals);  $N_X = 1.7202$ ,  $N_Y = 1.7380$ ,  $N_Z = 1.8197$ ,  $N_Z - N_X = 0.0995$  (artificial crystals). Color orange-red with X = reddish yellow, Y = yellow, Z = greenish yellow. Found in vugs in caliche in Chile.

## 8. Sulfates with type formula $A_m(BX_3)_n$

**Blakeite** [ $Fe_2(TeO_3)_3?$ ] is apparently isometric,<sup>142</sup> being isotropic (or nearly so) with  $N = 2.16$ .  $G. > 3.1$ . Color brown to yellow. Found at Goldfield, Nevada.

**Mackayite** [ $Fe_2(TeO_3)_3 \cdot nH_2O?$ ] is ditetragonal dipyramidal<sup>142</sup> with  $c/a = 1.26$ . Space group probably  $I4/acd$ ;  $a$  11.70,  $c$  14.95 Å. Crystals prismatic, with no cleavage.  $H. = 4.5$ .  $G. = 4.86$ . Uniaxial positive with  $N_O = 2.19$ ,  $N_E = 2.21$ ,  $N_E - N_O = 0.02$ . Color green with O = yellowish green, E = green. Found at Goldfield, Nevada.

**Chalcomenite** ( $CuSeO_3 \cdot 2H_2O$ ) is orthorhombic disphenoidal<sup>143</sup> with  $a:b:c = 0.733:1:0.808$ . Space group  $P2_12_12_1$ ;  $a$  6.65,  $b$  9.10,  $c$  7.36 Å. U.C. 4. Crystals small prismatic with base. No cleavage.  $H. = 2.5$ .  $G. = 3.35$ .  $F. = 1.5$ . Soluble in acid. The optic plane is 001 in red light with  $(- )2V = 34^\circ$  Li;  $2V = 0^\circ$  in green light; the optic plane is 010 in blue light with  $(- )2V = 10^\circ$ .  $X = a$ .  $N_X = 1.710$ ,  $N_Y = 1.731$ ,  $N_Z = 1.732$ ,  $N_Z - N_X = 0.022$ . Color blue; pale greenish blue; not pleochroic in thin section, but in plates  $X =$  light blue,  $Y = Z =$  darker blue. Found in copper ores at Mendoza, Argentina.

**Emmonsite** [ $Fe_2(TeO_3)_3 \cdot 2H_2O?$ ] is monoclinic<sup>142</sup> in fibers or plates with perfect 010 and poor (100 and 001?) cleavages.  $H. = 5$ .  $G. = 4.52$ . Soluble in HCl. The optic plane is 010; X nearly normal ( $82^\circ$ ) to poorer imperfect cleavage and at  $13^\circ$  to the other.  $(- )2V = 20^\circ$ ,  $r > v$  strong.  $N_X = 1.95$ ,  $N_Y = 2.09 \pm$ ,  $N_Z = 2.10$ ,  $N_Z - N_X = 0.15$ . Again  $N_X = 1.962$ ,  $N_Z = 2.12$ ,  $N_Z - N_X = 0.158$  and  $N_X = 1.965$ ,  $N_Z = 2.09$ . Color yellow-green; colorless in section. Found in Arizona and Nevada.

## 9. Sulfates with salts of other acids

### (a) ANHYDROUS

**Tychite** ( $2MgCO_3 \cdot 2Na_2CO_3 \cdot Na_2SO_4$ ) is isometric diploidal;<sup>144</sup> space group  $Fd\bar{3}$ ;  $a$  13.87 Å. U.C. 8. Crystals octahedral.  $H. = 3.5$ .  $G. = 2.46$  (natural); 2.49

<sup>141</sup> M. C. Bandy: *Am. Mineral.*, XXII, 929 (1937).

<sup>142</sup> C. Frondel and F. H. Pough: *Am. Mineral.*, XXIX, 211 (1944).

<sup>143</sup> C. Palache: *Am. Mineral.*, XXII, 790 (1937).

<sup>144</sup> T. Watanabe: *Min. Abst.*, V, 451 (1934).



(artificial).  $F. = 1$ . Soluble in acid. Isotropic with  $N = 1.508$ . Colorless. Found at Borax Lake, California, with northupite.

**Hanksite** <sup>145</sup> ( $KCl \cdot 2Na_2CO_3 \cdot 9Na_2SO_4$ ) is hexagonal dipyramidal with  $c/a = 2.02$ . Space group  $C6_3/m$  (or  $C6_3?$ );  $a$  10.46,  $c$  21.18 Å. Hexagonal U.C. 2. Crystals prismatic, or basal tablets; also pyramidal. Distinct basal cleavage.  $H. = 3$ .  $G. = 2.56$ .  $F. = 1.5$ . Soluble in water. Uniaxial negative with  $N_O = 1.4807$ ,  $N_E = 1.4614$ ,  $N_O - N_E = 0.0193$ . Colorless. Found at Borax Lake, California, etc.

**Corkite** [ $PbFe_3(OH)_6PO_4SO_4$ ] is hexagonal scalenohedral, with distinct basal cleavage.  $H. = 4$ .  $G. = 4.2$  ca. Soluble in HCl. Uniaxial negative with  $N_O = 1.93$ ,  $N_O - N_E =$  weak. Also biaxial with  $X = c$ ; basal sections show six biaxial segments. Color olive green, yellow to black. Abnormal green interference colors. Found with limonite. Very rare.

**Hinsdalite** [ $PbAl_3(OH)_6PO_4SO_4$ ] is hexagonal scalenohedral with  $c/a = 1.268$ . Perfect basal cleavage.  $H. = 4.5$ .  $G. = 4.65$ .  $F. = 7$ . Insoluble in HCl. Uniaxial positive with  $N_O = 1.670$ ,  $N_E = 1.689$ ,  $N_E - N_O = 0.019$ . Usually biaxial with  $Z = c$  and  $(+ )2V = 0^\circ - 30^\circ$ ; basal sections may show an isotropic center and six biaxial segments each having the optic plane normal to the edge.  $N_X = 1.670$ ,  $N_Y = 1.671$ ,  $N_Z = 1.689$ ,  $N_Z - N_X = 0.019$ . Color white, gray. Found in Hinsdale County, Colorado.

**Svanbergite** <sup>146</sup> [ $SrAl_3(OH)_6PO_4SO_4$ ] is hexagonal scalenohedral with  $c/a = 2.414$ .  $a$  6.96,  $c$  16.8 Å. Hexagonal U.C. 3. Perfect basal cleavage.  $H. = 5$ .  $G. = 3.2$ .  $F. = 6$ . Difficultly soluble in HCl. Uniaxial positive with  $N_O = 1.64$ ,  $N_E - N_O = 0.01$ . Again: <sup>147</sup>  $N_O = 1.635$ ,  $N_E = 1.649$ ,  $N_E - N_O = 0.014$ . Also biaxial with  $Z = c$ ; basal section shows six biaxial segments. Color yellow to brown or pink. Colorless in section. Found in mines in Sweden.

**Woodhouseite** <sup>148</sup> [ $CaAl_3(OH)_6PO_4SO_4$ ] is hexagonal scalenohedral with <sup>146</sup>  $c/a = 2.338$ .  $a$  6.96,  $c$  16.3 Å. Hexagonal U.C. 3. Crystals rhombohedral, or basal plates, with perfect basal cleavage.  $H. = 4.5$ .  $G. = 3.01$ . Soluble in HCl. Uniaxial positive with  $N_O = 1.636$ ,  $N_E = 1.647$ ,  $N_E - N_O = 0.011$ . Also biaxial with  $2V$  attaining  $20^\circ$  and the optic plane normal to the edges of the hexagonal outline of the cyclic twin. Related to beudantite. Found in quartz veins in Mono County, California.

**Beudantite** [ $PbFe_3(OH)_6AsO_4SO_4$ ] is hexagonal scalenohedral with  $c/a = 1.184$ . Crystals rhombohedral, with distinct basal cleavage.  $H. = 4$ .  $G. = 4.1 \pm$ .  $F. = 3.5$ . Soluble in HCl. Uniaxial negative with  $N_O = 1.96$ ,  $N_O - N_E =$  moderate or weak. Also biaxial with  $(- )2V =$  medium, with abnormal dispersion;  $X = c$ ; basal sections show six biaxial segments with lamellar twinning parallel to the edges. Color olive, yellow, brown to black; nearly colorless in section; also <sup>149</sup> golden yellow in section with  $X$  and  $Y < Z$ . Abnormal green interference colors. Alters to a brown mineral of higher relief which is strongly pleochroic with  $X' =$  dark brown and  $Z' =$  nearly colorless. Found with limonite in iron deposits, as at Dernbach, Nassau.

**Burkeite** <sup>150</sup> ( $Na_2CO_3 \cdot 2Na_2SO_4$ ) is orthorhombic with  $a:b:c = 0.574:1:?$ . Twinning on 110. No cleavage.  $H. = 3.5$ .  $G. = 2.57$ . The optic plane is 100;  $X = c$ .

<sup>145</sup> L. S. Ramsdell: *Am. Mineral.*, XXIV, 109 (1939).

<sup>146</sup> A. Pabst: *Am. Mineral.*, XXXII, 16 (1947).

<sup>147</sup> G. Switzer: *Am. Mineral.*, XXXIV, 104 (1949).

<sup>148</sup> D. M. Lemmon: *Am. Mineral.*, XXII, 939 (1937).

<sup>149</sup> A. Lacroix: *Minéral. France*, IV (1910).

<sup>150</sup> W. F. Foshag: *Am. Mineral.*, XX, 50 (1935).



(-) $2V = 34^\circ$ ,  $r > v$ .  $N_X = 1.448$ ,  $N_Y = 1.489$ ,  $N_Z = 1.493$ ,  $N_Z - N_X = 0.045$ . Colorless. Artificially it has been found<sup>151</sup> that burkeite can take about 25 mol. %  $3Na_2CO_3$  in crystal solution and then  $N_X = 1.445$ ,  $N_Y = 1.495$ ,  $N_Z = 1.497$ ,  $N_Z - N_X = 0.054$ ; or it can take about 10 mol. %  $3Na_2SO_4$  in crystal solution and then  $N_X = 1.465$ ,  $N_Y = 1.486$ ,  $N_Z = 1.488$ ,  $N_Z - N_X = 0.023$ . Artificial  $Na_2CO_3 \cdot 2Na_2SO_4$  has<sup>150</sup>  $N_X = 1.451$ ,  $N_Y = 1.489$ ,  $N_Z = 1.491$ ,  $N_Z - N_X = 0.040$ . Burkeite has been found at Searles Lake, California.

**Caledonite**<sup>152</sup>  $[Cu_2Pb_5(OH)_6CO_3(SO_4)_3]$  is orthorhombic dipyramidal with  $a:b:c = 0.356:1:0.326$ . Space group  $Pnmm$ ;  $a$  7.14,  $b$  20.06,  $c$  6.55 Å. U.C. 2. Crystals elongated along  $c$ ; perfect 010 and distinct 100 cleavages.  $H. = 2.5-3$ .  $G. = 5.76$ .  $F. = 1.5$ . Partly soluble in  $HNO_3$ . The optic plane is 100;  $X = c$ . (-) $2V = 85^\circ$ ,  $r < v$  weak.  $N_X = 1.818$ ,  $N_Y = 1.866$ ,  $N_Z = 1.909$ ,  $N_Z - N_X = 0.091$ . Color bluish green with  $Y < X$  and  $Z$  in blue tints. Found in lead ore deposits at Beaver Creek, Utah. Differs from linarite in giving a centered interference figure (obtuse bisectrix) from the best cleavage.

**Wherryite**<sup>153</sup>  $[CuO \cdot Pb(Cl,OH)_2 \cdot PbCO_3 \cdot 2PbSO_4]$  is a finely granular mineral with  $G. = 6.45$ . (-) $2V = 50^\circ$ ,  $N_X = 1.942$ ,  $N_Y = 2.010$ ,  $N_Z = 2.024$ ,  $N_Z - N_X = 0.082$ . Color light green. Found in a vug in Arizona.

**Vauquelinite**<sup>154</sup>  $[(Pb,Cu)_5O(PO_4)_2(CrO_4)_2]$  is monoclinic with  $a:b:c = 0.745:1:1.419$ ,  $\beta = 110^\circ 10'$ . Crystals fibrous or wedge-shaped; also concretionary. No cleavage. Twinning on 102.  $H. = 2.5-3$ .  $G. = 6 \pm$ .  $F. = 2(?)$ . Soluble in  $H_2SO_4$ .  $X$  nearly parallel to fibers. (-) $2V =$  nearly  $0^\circ$ , but biaxial.  $N_X = 2.11$ ,  $N_Y$  nearly  $= N_Z = 2.22$ ,  $N_Z - N_X = 0.11$ . In part nearly colorless; in part brown to green with  $X =$  pale green,  $Y = Z =$  pale brown and  $X < Y = Z$ . Found with lead ores, as in the Urals, and in Lancaster County, Pennsylvania. The reactions, color, and form are quite distinctive among vein minerals.

**Leadhillite**  $[Pb_4(OH)_2(CO_3)_2SO_4]$  is monoclinic prismatic with  $a:b:c = 1.752:1:2.226$ ,  $\beta = 90^\circ 28'$ . Crystals basal tablets. Pseudohexagonal twinning on 110; also on 310 as lamellae. Perfect basal cleavage.  $H. = 2.5$ .  $G. = 6.3-6.6$ .  $F. = 1.5$ . Effervesces in  $HNO_3$ . The optic plane is normal to 010;  $X \wedge c = +5\frac{1}{2}^\circ$ . (-) $2V = 10^\circ$ ,  $r < v$  strong.  $N_X = 1.87$ ,  $N_Y = 2.00$ ,  $N_Z = 2.01$ ,  $N_Z - N_X = 0.14$ . Optic axial angle decreases with heat, becoming  $0^\circ$  at  $130^\circ C.$  and remaining so; at  $-112^\circ C.$ ,  $2E = 28^\circ$ . Colorless. Found with lead ores in Scotland, etc.

## (b) HYDROUS

**Thaumasite**  $(CaSiO_3 \cdot CaCO_3 \cdot CaSO_4 \cdot 14.5H_2O)$  is hexagonal with  $c/a = 0.948$ . Space group  $C6_3$  or  $C6_3/m$ ;  $a$  10.90,  $c$  10.29 Å. U.C. 2. Crystals acicular to filiform.  $H. = 3.5$ .  $G. = 1.91$ .  $F. = 7$ . Attacked by acid. Uniaxial negative with  $N_O = 1.507$ ,  $N_E = 1.468$ ,  $N_O - N_E = 0.039$  (Lacroix);  $N_O = 1.500$ ,  $N_E = 1.464$ ,  $N_O - N_E = 0.036$  (Schaller). Colorless. A secondary mineral in trap, etc.

**Sulfoborite**  $(HMgBO_3 \cdot 2MgSO_4 \cdot 7H_2O)$  is orthorhombic dipyramidal with  $a:b:c = 0.62:1:0.81$ . Crystals prismatic, variable. Distinct 110 and 001 cleavages.  $H. = 2$ .  $G. = 2.4$ . Fusible. Soluble in water. Optic plane is 010;  $X = c$ . (-) $2V$

<sup>151</sup> W. C. Schroeder, A. A. Berk, and A. Gabriel: *J. Am. Chem. Soc.*, LVIII, 843 (1936).

<sup>152</sup> C. Palache and W. E. Richmond: *Am. Mineral.*, XXIV, 441 (1939).

<sup>153</sup> J. J. Fahey, E. B. Daggett, and S. G. Gordon: *Am. Mineral.*, XXXV, 93 (1950).

<sup>154</sup> E. F. Chirva: *Min. Abst.*, VII, 460 (1940).

=  $70^\circ \pm$ ;  $N_X = 1.527$ ,  $N_Y = 1.540$ ,  $N_Z = 1.544$ ,  $N_Z - N_X = 0.017$ . Colorless. Found in salt deposits.

**Lossenite** <sup>155</sup>  $[\text{Pb}_4\text{Fe}_{18}(\text{OH})_{18}(\text{AsO}_4)_{12}(\text{SO}_4)_4 \cdot 15\text{H}_2\text{O}]$  is orthorhombic with  $a:b:c = 0.84:1:0.95$ . Crystals acute pyramidal.  $H. = 3-4$ .  $F. = 2-2.5$ . Soluble in acid. The optic plane is 100;  $X = b$ .  $(+ )2V = 50^\circ$ ,  $r > v$  strong.  $N_X = 1.783$ ,  $N_Y = 1.788$ ,  $N_Z = 1.818$ ,  $N_Z - N_X = 0.035$ . Color brownish red. Found at Laurium, Greece.

**Schroëckingerite** <sup>156</sup>  $[\text{NaCa}_3\text{UO}_2\text{SO}_4(\text{CO}_3)_3\text{F} \cdot 10\text{H}_2\text{O}]$  is perhaps monoclinic. Crystals six-sided plates with micaceous basal cleavage.  $H. = 2.5$ .  $G. = 2.51$ .  $X$  is sensibly normal to the cleavage.  $(- )2V = 5^\circ$  (to  $25^\circ$  or even  $40^\circ$ ).  $N_X = 1.489$ ,  $N_Y = 1.542$ ,  $N_Z = 1.542$ ,  $N_Z - N_X = 0.053$ . Pleochroic with  $X =$  very pale yellow,  $Y$  and  $Z =$  pale greenish yellow. Strongly fluorescent in bright yellowish green in ultraviolet light. Weakly radioactive. Found with uraninite (as an alteration product?) or with gypsum.

**Darapskite** <sup>157</sup>  $(\text{NaNO}_3 \cdot \text{Na}_2\text{SO}_4 \cdot \text{H}_2\text{O})$  is monoclinic prismatic with  $a:b:c = 1.526:1:0.751$ ,  $\beta = 102^\circ 55'$ . Crystals {001} tablets; twinning on 100. Perfect 100 and 010 cleavages.  $H. = 2-3$ .  $G. = 2.2$ . Soluble in water. The optic plane is normal to 010;  $Z \wedge c = 12^\circ$ .  $(- )2V = 27^\circ$ ,  $r > v$  rather strong.  $N_X = 1.391$ ,  $N_Y = 1.481$ ,  $N_Z = 1.486$ ,  $N_Z - N_X = 0.095$ . Colorless. Lamellar twinning as in plagioclase. Found on the desert of Atacama.

**Sarmientite** <sup>158</sup>  $[\text{Fe}_4(\text{OH})_2(\text{AsO}_4)_2(\text{SO}_4)_2 \cdot 11\text{H}_2\text{O}]$  is monoclinic prismatic with  $a:b:c = 0.342:1:0.524$ ,  $\beta = 97^\circ 39'$ . Space group  $P2/m$ . Closely related to destinezite.  $G. = 2.58$ .  $Y = b$ ;  $Z \wedge c = 12^\circ$ .  $(+ )2V = 40^\circ$  calc.  $N_X = 1.628$ ,  $N_Y = 1.635$ ,  $N_Z = 1.689$ ,  $N_Z - N_X = 0.061$ . Color pale yellow. Found in iron sulfate deposits in Chile.

**Pitticite**  $(\text{Fe}_2\text{O}_3, \text{As}_2\text{O}_3, \text{SO}_3, \text{H}_2\text{O})$  is optically isotropic, but possibly the same as sarmientite. Conchoidal fracture.  $H. = 2-3$ .  $G. = 2.2-2.5$ .  $F. =$  easy. Soluble in  $\text{HCl}$ . Isotropic with  $N = 1.635 \pm$ . Color brown to white; reddish brown in section. Described as a colloidal mixture with  $N = 1.615-1.617$  by Foshag and Clinton.<sup>159</sup> Found about old mines, as in Saxony and Utah.

**Destinezite**  $[\text{Fe}_4(\text{OH})_2(\text{PO}_4)_2(\text{SO}_4)_2 \cdot 11\text{H}_2\text{O}]$  is monoclinic in six-sided tablets. Closely related to sarmientite.  $H. = 3$ .  $G. = 2.1$ .  $F. = 6$ . Soluble in  $\text{HCl}$ . According to Lacroix<sup>149</sup> the optic plane is 010;  $X \wedge a = -39^\circ$ ;  $Z \wedge c = 15^\circ$ ;  $N$  is between 1.64 and 1.66,  $N_Z - N_X = 0.026-0.030$ . According to Larsen<sup>3</sup>  $X$  is not quite normal to 010;  $Z \wedge$  elongation  $= 16^\circ$ ;  $(+ )2V =$  small,  $r > v$  rather strong;  $N_X = 1.615$ ,  $N_Y = 1.625$ ,  $N_Z = 1.665$ ,  $N_Z - N_X = 0.050$ . Color white. *Arsenian destinezite* <sup>160</sup> has  $Z \wedge$  elongation  $= 18^\circ$ ;  $N_1 = 1.626$ ,  $N_2 = 1.570$ . Found in Bel-

<sup>155</sup> L. Milch: *Zeit. Krist.*, XXIV, 100 (1895); considered a mixture by Lacroix: *Bull. Soc. Fr. Min.*, XXXVIII, 35 (1915).

<sup>156</sup> "Dakeite," described by E. S. Larsen and F. A. Gonyer: *Am. Mineral.*, XXII, 561 (1937), is considered a synonym of schroëckingerite by R. Nováček: *Am. Mineral.*, XXIV, 317 (1939). See also H. W. Jaffe *et al.*, *Am. Mineral.*, XXXIII, 152 (1948).

<sup>157</sup> E. S. Larsen: *U. S. Geol. Surv. Bull.* 679 (1921); O. W. Jarrell: *Am. Mineral.*, XXIV, 629 (1939).

<sup>158</sup> V. Angelelli and S. G. Gordon: *Am. Mineral.*, XXVII, 333 (1942); *Not. Nat. Acad. Sci. Phila.*, 92, 1941.

<sup>159</sup> W. F. Foshag and H. G. Clinton: *Am. Mineral.*, XII, 290 (1927).

<sup>160</sup> F. Ulrich: *Min. Abst.*, V, 86 (1932).

gium. *Diadochite* is similar but may contain more water. It is isotropic with  $N = 1.618-1.70+$ . Color brown or yellow opaline; colorless to yellow in section. Found in alum-bearing slate and in coal mines, as at Isère, France.

**Lindackerite**  $[\text{Ni}_3\text{Cu}_6(\text{OH})_4(\text{AsO}_4)_4\text{SO}_4 \cdot 5\text{H}_2\text{O}]$  is monoclinic(?). Crystals {010} tablets, or fibrous. Perfect 010 cleavage.  $H. = 2-2.5$ .  $G. = 2-2.5$ . Soluble in HCl. The optic plane is 010;  $X \wedge$  elongation =  $26^\circ$ .  $(+)2V = 73^\circ$ ,  $r < v$  strong.  $N_X = 1.629$ ,  $N_Y = 1.662$ ,  $N_Z = 1.727$ ,  $N_Z - N_X = 0.098$ . Color apple green. Found in Bohemia.

## IX. PHOSPHATES

This division includes phosphates, arsenates, antimonates, and vanadates. A few double salts (of phosphoric and some other acid) are included. The arrangement is based on the formula type, depending, first, on the ratio of B to X in the general formula  $A_mB_nX_p$ , and second, on the increasing ratio of A to B. In this division anions which are not part of the phosphate acid radical are important; therefore subdivisions are recognized for such cases as well as for hydrous and anhydrous types. Unfortunately many minerals of this division have been studied only partially and their composition and properties are so incompletely known that their classification is quite uncertain. An outline classification follows:

1. Type formula  $\approx ABX_4$   $\left\{ \begin{array}{l} (a) \text{ Anhydrous.} \\ (b) \text{ Hydrous.} \end{array} \right.$
2. Type formula  $\approx A_3B_2X_8$   $\left\{ \begin{array}{l} (a) \text{ Without additional anions } \left\{ \begin{array}{l} \text{Anhydrous.} \\ \text{Hydrous.} \end{array} \right. \\ (b) \text{ With additional anions } \left\{ \begin{array}{l} \text{Anhydrous.} \\ \text{Hydrous.} \end{array} \right. \end{array} \right.$
3. Type formula  $\approx A_2BX_4$   $\left\{ \begin{array}{l} (a) \text{ Without additional anions } \left\{ \begin{array}{l} \text{Anhydrous.} \\ \text{Hydrous.} \end{array} \right. \\ (b) \text{ With additional anions } \left\{ \begin{array}{l} \text{Anhydrous.} \\ \text{Hydrous.} \end{array} \right. \end{array} \right.$
4. Type formula  $\approx A_5B_2X_8$   $\left\{ \begin{array}{l} (a) \text{ Without additional anions.} \\ (b) \text{ With additional anions } \left\{ \begin{array}{l} \text{Anhydrous.} \\ \text{Hydrous.} \end{array} \right. \end{array} \right.$
5. Type formula  $A_mBX_4$  with  $m \approx 3$  or more  $\left\{ \begin{array}{l} (a) \text{ Without additional anions.} \\ (b) \text{ With additional anions } \left\{ \begin{array}{l} \text{Anhydrous.} \\ \text{Hydrous.} \end{array} \right. \end{array} \right.$
6. Type formula  $A_2B_2X_7$ .
7. Type formula  $A_m(BX_3)_n$ .

1. Phosphates with type formula  $\approx \text{ABX}_4$ 

## (a) ANHYDROUS

**XENOTIME**DITETRAGONAL DIPYRAMIDAL  $c/a = 0.618$ **YPO<sub>4</sub>**

COMP. Y may be replaced in part by Er, Ce, etc.; Si and Th may be present in small amount.

STRUC. Space group <sup>1</sup>  $F4/ddm$ ;  $a$  9.375,  $c$  6.013 Å. For the smallest cell,  $a = 6.88$  Å, space group symbol  $I4/amd$ .

PHYS. CHAR. Crystals prismatic like zircon; twinning on 101. Perfect 110 cleavage.  $H. = 4-5$ .  $G. = 4.59$ .  $F. = 7$ . Insoluble in HCl.

OPT. PROP. Uniaxial positive with  $N_O = 1.7207$ ,  $N_E = 1.8155$ ,  $N_E - N_O = 0.0948$ . Again: <sup>2</sup>  $N_O = 1.720$ ,  $N_E = 1.827$ ,  $N_E - N_O = 0.107$ . Color yellowish brown to red, gray, yellow. Streak paler. Luster resinous to vitreous. In thin section colorless, yellowish, brownish; may be weakly pleochroic with  $O =$  pink or light yellowish brown,  $E =$  brownish yellow or grayish brown.

OCCUR. Xenotime is found in pegmatite and granite, usually associated with zircon.

DIAG. It differs from zircon in hardness and composition; from cassiterite in weaker refringence, and from anatase in optic sign. Differs from bastnäsite in being unaffected by heating to redness for one minute.

**Berlinite** ( $\text{AlPO}_4$ ) is trigonal trapezohedral <sup>3</sup> with  $c/a = 2.217$ . Space group  $C3_12$  or  $C3_22$ .  $a$  4.92,  $c$  10.91 Å. U.C. 3.  $H. = 6-7$ .  $G. = 2.64$ . Uniaxial and positive with  $N_O = 1.5235$ ,  $N_E = 1.529$ ,  $N_E - N_O = 0.0055$ . Isotypic with quartz. Found in Sweden.

**Pucherite** ( $\text{BiVO}_4$ ) is orthorhombic <sup>4</sup> with  $a:b:c = 0.449:1:0.421$ .  $a$  5.38,  $b$  11.98,  $c$  5.04 Å. U.C. 4. Crystals thick {010} tablets or acicular, with perfect 010 cleavage.  $H. = 4$ .  $G. = 6.25$ .  $F. = 2$ . Soluble in HCl.  $X = b$ ,  $Z = a$ .  $(- )2V = 19^\circ$ ,  $r > v$  extreme.  $N_X = 2.41$ ,  $N_Y = 2.50$ ,  $N_Z = 2.51$ ,  $N_Z - N_X = 0.10$  (Li). Color reddish brown. Found in ore deposits, as at the Pucher mine in Saxony.

**Heterosite** <sup>5</sup> [ $(\text{Fe}''', \text{Mn}''')\text{PO}_4$ ] is orthorhombic dipyramidal with  $a:b:c = 0.492:1:0.602$ . Space group  $Pnma$ ;  $a$  4.76,  $b$  9.68,  $c$  5.82 Å. Often contains Li and  $\text{H}_2\text{O}$ . With  $\text{Mn} > \text{Fe}$ , called *purpurite* by Schaller; <sup>6</sup> but purpurite of some authors contains Na.<sup>7</sup>  $H. = 3.5-4.5$ .  $G. = 3.3-3.5$ .  $F. =$  easy. Soluble in HCl. The optic plane is 100;  $X = c$ .  $(\pm)2V = 38-90^\circ$ ,  $N_X = 1.83-1.86$ ,  $N_Y = 1.86-1.92$ ,  $N_Z = 1.9-1.92$ ,  $N_Z - N_X = 0.03-0.07$ . Color deep red, purple, violet, black, with  $X =$  gray, brown, or reddish brown,  $Y =$  deep red, scarlet, or carmine,  $Z =$  purple, dark violet or dark red. An alteration product of triplite-lithiophilite, as at Limoges, France.

<sup>1</sup> L. Vegard: *Phil. Mag.*, IV, 511 (1927).

<sup>2</sup> C. O. Hutton: *Am. Mineral.*, XXXII, 141 (1947).

<sup>3</sup> H. Strunz: *Zeit. Krist.*, CIII, 228 (1941).

<sup>4</sup> W. F. De Jong and J. J. De Lange: *Am. Mineral.*, XXI, 809 (1936);  $c$  and  $b$  interchanged to make  $b > a > c$ .

<sup>5</sup> B. Mason: *Geol. För. Förh.*, LXIII, 117 (1941). P. Quensel: *Geol. För. Förh.*, LIX, 77 (1937).

<sup>6</sup> W. T. Schaller: *J. Wash. Acad. Sci.*, I, 113 (1911).

<sup>7</sup> C. O. Björling and A. Westgren: *Geol. För. Förh.*, LX, 67 (1938). *Chem. Abst.*, XXXII, 3729 (1938).

## MONAZITE

## MONOCLINIC PRISMATIC



$$a:b:c = 0.969:1:0.915 \quad \beta = 103^\circ 54'$$

COMP. Ce is often replaced by La, Nd, Pr, Er, etc., sometimes in large part; Th and Si usually also present, perhaps as  $\text{ThSiO}_4$ .

STRUC. Space group  $P2_1/c$ ;  $a$  6.782,  $b$  6.993,  $c$  6.455 Å. U.C. 4. With  $^9\text{Ce:La:Y} = 4:4:1$ ,  $a$  6.76,  $b$  7.00,  $c$  6.42 Å,  $\beta = 103^\circ 10'$ .

PHYS. CHAR. Crystals small {100} tablets or elongated along  $b$ ; perfect 001 and distinct 100 cleavages. Twinning on 100.  $H. = 5$ .  $G. = 5.1$  ca.  $F. = 7$ . Difficultly soluble in HCl.

OPT. PROP. The optic plane is normal to 010;  $Z \wedge c = -1^\circ$  to  $-6^\circ$ . See Fig. 107.  $(+2V) = 6^\circ-19^\circ \text{Na}$ ;  $r < v$  very weak, varying to  $r > v$  very weak, with weak horizontal dispersion.  $N_X = 1.787-1.801$ ,  $N_Y = 1.788-1.801$ ,  $N_Z = 1.837-1.849$ ,  $N_Z - N_X = 0.045-0.055$ . Without  $^{10}\text{ThO}_2$ ,  $G. = 5.17$ ,  $N_X = 1.785$ ,  $N_Y = 1.787$ ,  $N_Z = 1.840$ ,  $N_Z - N_X = 0.055$ .

Color yellowish to reddish brown or red; not pleochroic in section, but absorption is distinct with  $Y > X = Z$ .

OCCUR. Monazite is a sparse accessory constituent of some granite, aplite, and pegmatite; also in sands derived from such rocks.

DIAG. It differs from olivine in its very small optic angle; from titanite in its much weaker birefringence and very weak dispersion. In sands it may be distinguished from zircon by its yellow color, variable absorption in yellow, and biaxial character, and from epidote by weaker absorption and small optic angle.

**Roseveltite**<sup>11</sup> ( $\text{BiAsO}_4$ ) is monoclinic(?). It has conchoidal fracture, no cleavage.  $H. = 4-5$ .  $G. = 6.86$ .  $N > 1.74$ ;  $N_Z - N_X = \text{strong}$ .

## (b) HYDROUS

**Arsenobismite**<sup>12</sup> ( $\text{BiAsO}_4 \cdot n\text{H}_2\text{O}$ ?) is isometric(?) in cryptocrystalline aggregates.  $G. = 5.7$ . Isotropic (or nearly so) with  $N$  above 1.86. Also reported as  $N = 1.6$ . Yellowish green to yellowish brown. Found at Tintic, Utah, and at Tazna, Bolivia.

**Rhabdophanite** [ $\text{La,Nd,Pr,Y,ErPO}_4 \cdot \text{H}_2\text{O}$ ] is tetragonal or hexagonal. Fibrous.  $H. = 3.5$ .  $G. = 4$ .  $F. = 7$ . Soluble in acid. Uniaxial positive with  $N_O = 1.654$ ,  $N_E = 1.703$ ,  $N_E - N_O = 0.049$ . Color brown to white. Resembles brown sphalerite. Found in Cornwall.

<sup>8</sup> S. V. Gliszczynski: *Zeit. Krist.*, CI, 1 (1939); W. Parrish: *Am. Mineral.*, XXIV, 651 (1939).

<sup>9</sup> W. Parrish: *Am. Mineral.*, XXIV, 651 (1939).

<sup>10</sup> S. G. Gordon: *Min. Abst.*, VII, 508 (1940).

<sup>11</sup> R. Herzenberg: *Tech. Bull. Univ. Oruro*, 1 (1946).

<sup>12</sup> C. Frondel: *Am. Mineral.*, XXVIII, 536 (1943).

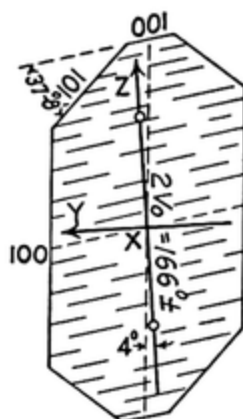


FIG. 107. The optic orientation of monazite.



SCORODITE

ORTHORHOMBIC DIPYRAMIDAL



$a:b:c = 1.031:1:0.897$ <sup>13</sup>

COMP. P may proxy for some As. The Al end-member has been named *mansfieldite*.<sup>14</sup>

STRUC. Space group<sup>15</sup>  $Pcab$ ;  $a$  10.30,  $b$  10.00,  $c$  8.90 Å. U.C. 4. The atomic arrangement is related to that of phosphosiderite-metavariscite.

PHYS. CHAR. Crystals pyramidal, prismatic, or {001} tablets. Poor 201, and traces of 010 and 001 cleavages.  $H. = 3.5-4$ .  $G. = 3.1-3.4$ .  $F. = 2-2.5$ . Soluble in HCl.

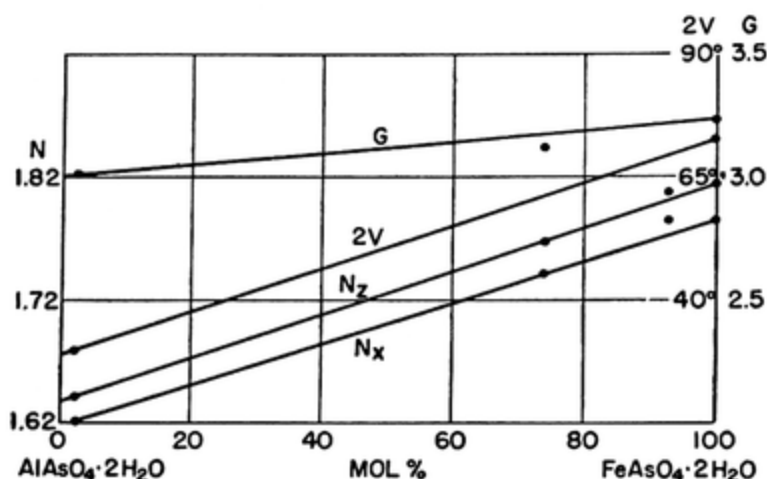


FIG. 107a. Properties of the mansfieldite-scorodite series.

OPT. PROP. The optic plane is 100;  $X = c$ .  $(+ )2V = 50^\circ-70^\circ$ ,  $r > v$  strong. Considerable variation in indices (see Fig. 107a), due to variations in composition, as follows:

$\text{As}_2\text{O}_5$	$\text{P}_2\text{O}_5$	$\text{Fe}_2\text{O}_3$	$\text{Al}_2\text{O}_3$	2V	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$	Authors
49.52	0.0	34.79	0.0	(+)75°	1.784	1.795	1.814	0.030	Allen and Fahey <sup>14</sup>
48.42		34.3	0.0	(+)54°	1.784	1.796	1.814	0.030	Foshag <sup>16</sup>
48.96		34.2	1.60	(+)Med.	1.787	1.795	1.810	0.023	Foshag <sup>17</sup>
48.88	1.72	25.72	5.76	(+)40°	1.741	1.744	1.768	0.057	Allen and Fahey <sup>14</sup>
26.12	16.03	40.32		(+)	1.758-1.762		1.777-1.789	0.019-0.027	Shadlun <sup>18</sup>
				?	1.712	?	1.728	0.016	Denning <sup>19</sup>
56.43	0.59	0.88	23.30	(+)30°	1.622	1.624	1.642	0.020	Allen and Fahey <sup>14</sup>

Color leek green to brown; weakly pleochroic in thick sections with  $X =$  colorless to pink,  $Z =$  (bluish) green. Also weakly pleochroic in yellow and green.

<sup>13</sup> H. Strunz and K. Sztrokay: *Zent. Min.*, 1939A, 272. The rule  $c < a < b$  is abandoned in this case to show the relationship with phosphosiderite.

<sup>14</sup> V. T. Allen and J. J. Fahey: *Am. Mineral.*, XXXI, 189 (1946); and XXXIII, 122 (1948).

<sup>15</sup> D. McConnell: *Am. Mineral.*, XXV, 719 (1940).

<sup>16</sup> W. F. Foshag, H. Berman and R. A. Doggett: *Am. Mineral.*, XV, 390 (1930).

<sup>17</sup> W. F. Foshag: *Am. Mineral.*, XXII, 479 (1937).

<sup>18</sup> J. N. Shadlun and V. S. Nesterova: *Chem. Abst.*, XLIII, 2898 (1949).

<sup>19</sup> R. M. Denning: *Am. Mineral.*, XXVIII, 55 (1943).

**OCCUR.** Scorodite is found with arsenopyrite, enargite, limonite, etc., in limestone; also in the oxide zone in veins; also about geysers. Not common.

**DIAG.** The color and the strong dispersion are rather characteristic.

**VARISCITE**ORTHORHOMBIC DIPYRAMIDAL <sup>15,20</sup>(Al,Fe)PO<sub>4</sub>·2H<sub>2</sub>O

$$a:b:c = 1.022:1:0.892$$

**COMP.** There is probably a continuous series from AlPO<sub>4</sub>·2H<sub>2</sub>O to FePO<sub>4</sub>·2H<sub>2</sub>O (called *strengite*); *barrandite* is an intermediate type. Mn<sup>+++</sup> is present in some cases; also a little Mg and Ca.

**STRUC.** Space group <sup>15</sup> *Pcab*; *a* 9.85, *b* 9.55, *c* 8.50 Å. for AlPO<sub>4</sub>·2H<sub>2</sub>O.

**PHYS. CHAR.** Crystals pyramidal or prismatic to fibrous, with perfect 010 and poor 001 cleavages. *H.* = 3–4. *G.* = 2.54–2.87, *F.* = 2–7. Soluble in HCl at least after ignition.

**OPT. PROP.** The optic plane <sup>21</sup> is 100; *X* = *c*. (–)2*V* = 30°–large, *r* > *v*; with more iron (+)2*V* = large to small, *r* < *v*, strong. Other data follow:

Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	Sign	2 <i>V</i>	N <sub>X</sub>	N <sub>Y</sub>	N <sub>Z</sub>	N <sub>Z</sub> – N <sub>X</sub>	Author
?	?	–	Mod. Large	1.550	1.565	1.570	0.020	Larsen <sup>22</sup>
27.34	2.20	–	Mod. Large	1.562	1.583	1.590	0.028	Larsen <sup>22</sup>
24.93	6.50	–	32° ±	1.566	1.584	1.593	0.027	Ulrich <sup>23</sup>
33.95		–	32°	1.578	1.590	1.599	0.021	Schoep <sup>24</sup>
?	?	–	Large	1.575	1.595	1.610	0.035	Gordon <sup>25</sup>

**BARRANDITE**

8.0	33.6	+	Small	?	1.57–1.58	?	0.015–0.017	Lacroix <sup>26</sup>
8.15	30.0	?	?	?	1.64	?	0.02	Shannon <sup>27</sup>
?	?	+	Large	?	1.65	?	0.03	Larsen <sup>28</sup>

**STRENGITE**

–	Mod.	1.697	1.714	1.722	0.025	Larsen <sup>28</sup>
?	?	1.71	?	1.735	0.025	Schaller <sup>29</sup>
+	Small	1.708	1.708	1.745	0.037	Larsen <sup>28</sup>
+	29°	1.730	1.732	1.762	0.032	Larsen <sup>28</sup>

Samples of strengite with a notable tenor of Mn<sup>+++</sup> have been called *vilatéite*; <sup>26</sup> they are optically negative with *N* = 1.74 *ca.* and *N<sub>Z</sub> – N<sub>X</sub>* = strong. A blue manganiferous strengite from Pala, California, has (–)2*V* = medium, *N<sub>X</sub>* = 1.697, *N<sub>Y</sub>* = 1.714, *N<sub>Z</sub>* = 1.722, *N<sub>Z</sub> – N<sub>X</sub>* = 0.025. Such samples are blue or violet with *X* = colorless or very pale violet, *Y* = clear violet, *Z* = dark blue. Other strengite is pink or colorless; it may be weakly pleochroic with *X* and *Y* colorless, *Z* = pale pink.

<sup>20</sup> P. Kokkoros: *Min. Abst.*, VIII, 140 (1941).

<sup>21</sup> Also reported as 010 by Lacroix, probably due to differing orientation of axes.

<sup>22</sup> E. S. Larsen and W. T. Schaller: *Am. Mineral.*, X, 23 (1925).

<sup>23</sup> F. Ulrich: *Min. Abst.*, V, 281 (1933).

<sup>24</sup> A. Schoep: *N. Jahrb. Min.*, I, 231 (1930).

<sup>25</sup> Personal communication, Dec. 17, 1924.

<sup>26</sup> A. Lacroix: *Minéral. France*, IV (1910).

<sup>27</sup> E. V. Shannon: *Am. Mineral.*, VIII, 182 (1923).

<sup>28</sup> E. S. Larsen: *U. S. Geol. Surv. Bull.* 679 (1921) and 848 (1934).

<sup>29</sup> W. T. Schaller: *U. S. Geol. Surv. Bull.* 610 (1916).

Strengite has a small optic angle with strong dispersion,  $r < v$ ; for example, a sample from Bavaria<sup>30</sup> has  $(+)\text{2E} = 30^\circ \text{ Li}$ ,  $46^\circ \text{ yellow}$ ,  $55^\circ \text{ green}$ ,  $110^\circ \text{ blue}$ .

Barrandite is gray, yellow, red, bluish, or green.

Variscite is green, blue, yellow, or white; colorless in section. On gentle heating the mineral loses water and then has  $N_X = 1.447$ ,  $N_Y = 1.448$ ,  $N_Z = 1.450$ ,  $N_Z - N_X = 0.003$ . The crystals are then lavender and strongly pleochroic with  $a (= Z) = \text{lavender}$ ,  $b = \text{pinkish lavender}$ ,  $c = \text{violet}$ ; the sign is probably positive and  $2V$  large.

**OCCUR.** Variscite is found in sedimentary rocks, as at Messbach, Saxony; strengite in pegmatites and iron ore deposits, as in Rockbridge County, Virginia.

**DIAG.** Strengite is characterized by pink color and strong dispersion; phosphosiderite has similar dispersion, but inclined extinction and large optic angle.

**Erikite**<sup>31</sup>  $[\text{H}_4\text{CaMg}(\text{Ce}, \text{Y})_{12}\text{Si}_2\text{P}_{12}\text{O}_{56} \cdot 13\text{H}_2\text{O}]$  is orthorhombic with  $a:b:c = 0.576:1:0.758$ . May contain more<sup>32</sup> Si. Pseudo-hexagonal and apparently uniaxial; without cleavage.  $H. = 2-3$ .  $G. = 3.78$ ,  $F. = 7$ .  $(+)\text{2V} = 0^\circ(?)$ .  $N_X = 1.70 \text{ ca.}$ ,  $N_Z = 1.73 \text{ ca.}$ ,  $N_Z - N_X = 0.02-0.03$ . Found in syenite in Greenland and the Kola Peninsula, U. S. S. R.

**Churchite**  $[\text{Ca}_3\text{Ce}_{10}(\text{PO}_4)_{12} \cdot 24\text{H}_2\text{O}]$  is orthorhombic(?); crystals rectangular tablets with bevels on the long edges; one perfect cleavage.  $H. = 3-3.5$ .  $G. = 3.14$ .  $F. = 7$ . Soluble in acid.  $Z$  normal to plates.  $(+)\text{2V} = 0^\circ$ , perceptibly;  $N_X = N_Y = 1.620$ ,  $N_Z = 1.665$ ,  $N_Z - N_X = 0.045$ . Colorless. Found in copper ore in Cornwall.

<b>PHOSPHOSIDERITE</b> <sup>15,33</sup>	MONOCLINIC	$\text{FePO}_4 \cdot 2\text{H}_2\text{O}$
<b>METAVARISCITE</b> <sup>15</sup>	MONOCLINIC	$\text{AlPO}_4 \cdot 2\text{H}_2\text{O}$
$a:b:c = 0.546:1:0.894 \quad \beta = 90^\circ 30'$		

**COMP.** There is probably a continuous series from  $\text{FePO}_4 \cdot 2\text{H}_2\text{O}$  to  $\text{AlPO}_4 \cdot 2\text{H}_2\text{O}$ , but evidence is lacking. *Clinobarrandite*<sup>19</sup> is an intermediate member of the series.

**STRUC.** Space group<sup>33</sup>  $P2_1/n(?)$ ; for  $\text{FePO}_4 \cdot 2\text{H}_2\text{O}$ :  $a$  5.30,  $b$  9.79,  $c$  8.67 Å; U.C. 4.  $a:b:c = 0.545:1:0.894$ ,  $\beta = 90^\circ 36'$ . For  $\text{AlPO}_4 \cdot 2\text{H}_2\text{O}$ :  $a$  5.15,  $b$  9.45,  $c$  8.45.

**PHYS. CHAR.** Crystals prismatic or {010} tablets, with perfect 010 and good 001 cleavages. Twinning on 101.  $H. = 3.5-4$ .  $G. = 2.54$  (for Al)-2.76 (for Fe). Soluble in HCl.

**OPT. PROP.** The optic plane is 010;  $X \wedge c = \text{very small to } +5^\circ$ .

	Sign	2V	Dispersion	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$	G
$\text{FePO}_4 \cdot 2\text{H}_2\text{O}$	—	$62^\circ$	$r > v$ strong	1.692	1.725	1.738	0.046	2.76
$\text{AlPO}_4 \cdot 2\text{H}_2\text{O}$	+	$55^\circ$	$r < v$ distinct	1.551	1.558	1.582	0.031	2.54

Phosphosiderite is pinkish red to reddish violet with  $X = \text{pale rose}$ ,  $Y = \text{carmine red}$ ,  $Z = \text{nearly colorless}$  (in thick plates); colorless in thin section. Metavariscite is green, blue, or white; colored irregularly, with  $X = \text{colorless}$ ,  $Y = Z = \text{pale green}$ . On gentle heating it loses water and changes to the same substance thus obtained from variscite.

<sup>30</sup> H. Laubmann and H. Steinmetz: *Zeit. Krist.*, LV, 523 (1920).

<sup>31</sup> V. I. Gerasimovsky: *Min. Abst.*, VIII, 222 (1942).

<sup>32</sup> O. B. Böggild: *Med. Grönland*, XXVI, 93 (1903).

<sup>33</sup> D. McConnell: *Am. Mineral.*, XXIV, 636 (1939), and XXV, 719 (1940).

**OCCUR.** Phosphosiderite is found in iron ore, as at Eiserfeld, Germany, and in pegmatite. Metavariscite is known only at Lucin, Utah.

**Weinschenckite**<sup>34</sup>  $[(\text{Er}, \text{Y})\text{PO}_4 \cdot 2\text{H}_2\text{O}]$  is monoclinic prismatic with  $a:b:c = 0.429:1:0.415$ ,  $\beta = 128^\circ 24'$ . Space group  $C2c(?)$ ;  $a$  6.48,  $b$  15.12,  $c$  6.28 Å. U.C. 4. Crystals acicular. Basal and  $\bar{1}01$  cleavages.  $G. = 3.1\text{--}3.27$ .  $F. = 7$ . Soluble in acid.  $X = b$ ,  $Z \wedge c = +28^\circ$  to  $+35^\circ$ .  $(+ )2V = \text{moderate}$ ,  $N_X = 1.605$ ,  $N_Y = 1.612$ ,  $N_Z = 1.645$ ,  $N_Z - N_X = 0.040$ . Colorless. When gently heated fluoresces in pink under mercury lamp. Found as coating on limonite in Bavaria and in Rockbridge County, Virginia.

**Koninckite**  $(\text{FePO}_4 \cdot 3\text{H}_2\text{O})$  is in fibrous crusts with transverse cleavage.  $H. = 3$ .  $G. = 2.3\text{--}2.5$ .  $F. = 2.5\text{--}3$ . Soluble in  $\text{HCl}$ .  $X$  parallel to elongation.  $N_X = 1.645$ ,  $N_Y = 1.65$ ,  $N_Z = 1.656$ ,  $N_Z - N_X = 0.011$ . Also isotropic with  $N = 1.65$ . Color yellow. Found at Richelle, Belgium.

**Fervanite**  $(4\text{FeVO}_4 \cdot 5\text{H}_2\text{O})$  is monoclinic(?); fibrous. No visible cleavage. Fibers have slightly inclined extinction.  $(- )2V = \text{very small}$ .  $N_X = 2.186$ ,  $N_Y = 2.222$ ,  $N_Z = 2.224$ ,  $N_Z - N_X = 0.038$ . Color golden brown in mass, with brilliant luster. Found in carnotite ores in Utah, etc.

**Steigerite**<sup>35</sup>  $(\text{AlVO}_4 \cdot 3\text{H}_2\text{O}?)$  is cryptocrystalline and powdery.  $N = 1.71 \pm 0.005$ . Color canary yellow. Probably a metacolloid. Found in cracks in sandstone in Gypsum Valley, Colorado.

## 2. Phosphates with type formula $\approx \text{A}_3\text{B}_2\text{X}_8$

### (a) WITHOUT ADDITIONAL ANIONS—ANHYDROUS

**Berzeliite**<sup>36</sup>  $[\text{NaCa}_2(\text{Mg}, \text{Mn})_2(\text{AsO}_4)_3]$  is isometric hexoctahedral; space group  $Ia\bar{3}d$ ;  $a$  12.35 (with 2.3 MnO) to 12.46 Å (with 19.4 MnO); similar to garnet. U.C. 8. Crystals rare; no cleavage.  $H. = 5$ .  $G. = 4.16\text{--}4.29$ .  $F. = 3$ . Soluble in  $\text{HNO}_3$ . Isotropic with  $N = 1.71$  (for Mg type) to 1.786 (for Mn type<sup>37</sup>);  $F - C = 0.012$  to 0.015. May be slightly anisotropic. Color sulfur to orange yellow. Found in ores, as at Långban, Sweden.

**Whitlockite**<sup>38</sup>  $(\text{Ca}_3\text{P}_2\text{O}_8)$  is hexagonal scalenohedral with  $c/a = 3.576$ . Space group probably  $R\bar{3}c$ ;  $a$  10.32,  $c$  36.9 Å. Hexagonal U.C. 24. May contain some Mg and  $\text{H}_2\text{O}$ ; probably may contain C, as in apatite. Crystals rhombohedral. No cleavage.  $H. = 5$ .  $G. = 3.0\text{--}3.2$ . Uniaxial negative with  $N_O = 1.629$ ,  $N_E = 1.626$ ,  $N_O - N_E = 0.003$ . Occasionally, it has indices as low as 1.600, apparently due to water. (Such material has been called *martinite*.) Colorless; but it is orange-yellow on cooling below red heat; then becomes yellow, and finally white below  $200^\circ \text{C}$ . Found in pegmatite, as at North Groton, New Hampshire. A high-temperature ( $\alpha$ ) phase<sup>39</sup> is biaxial with  $(+ )2V = 75^\circ$ ,  $N_X = 1.588$ ,  $N_Z = 1.591$ . It inverts to whitlockite at about  $1200^\circ \text{C}$ .

<sup>34</sup> C. Milton, K. J. Murata, and M. M. Knechtel: *Am. Mineral.*, XXIX, 92 (1944).

<sup>35</sup> E. P. Henderson: *Am. Mineral.*, XX, 769 (1935).

<sup>36</sup> W. Bubeck: *Geol. För. Förh.*, LVI, 525 (1934), and W. Bubeck and F. Machatschki: *Zeit. Krist.*, XC, 44 (1935).

<sup>37</sup> S. Landergren: *Geol. För. Förh.*, LII, 123 (1930).

<sup>38</sup> C. Frondel: *Am. Mineral.*, XXVI, 145 (1941), and XXVIII, 215 (1943); H. Strunz: *Naturw.*, XXX, 242 (1942).

<sup>39</sup> W. L. Hill, S. B. Hendricks, M. E. Jefferson, and D. S. Reynolds: *Ind. Eng. Chem.*, XXIX, 1299 (1937).

**Caryinite**  $[Ca_3(Mn,Mg,Pb)_3(AsO_4)_4]$  is orthorhombic with distinct 110 and 010 cleavages, the 110 cleavage angle being  $98^\circ 30'$ .  $H. = 3-3.5$ .  $G. = 4.25$ .  $F. = 2.5$ .  $X = c$ ;  $Y = a$ .  $(+)2V = 41^\circ$ ,  $r > v$  weak.  $N_X = 1.776$ ,  $N_Y = 1.780$ ,  $N_Z = 1.805$ ,  $N_Z - N_X = 0.029$ . Color nut brown, not pleochroic. Alters to berzelite. Found in contacts at Långban, Sweden.

**Sicklerite**<sup>40</sup>  $(LiMnPO_4 \cdot nFe'''PO_4)$  is orthorhombic dipyramidal with  $a:b:c = 0.475:1:0.589$ . Space group <sup>41</sup>  $Pnma$ ;  $a$  4.787,  $b$  10.086,  $c$  5.939 Å. U.C. 4. Two unequal cleavages at  $90^\circ$ .  $H. = 4$ .  $G. = 3.45$ .  $F. =$  easy. Soluble in acid.  $Z$  normal to best cleavage.  $(-)2V =$  rather large,  $r > v$  very strong. With  $Mn > Fe$ :  $N_X = 1.715$ ,  $N_Y = 1.735$ ,  $N_Z = 1.745$ ,  $N_Z - N_X = 0.030$ . With  $Fe > Mn$ :  $N_Y = 1.8$  ca. Color dark brown; pleochroic with  $X =$  deep reddish,  $Y =$  reddish,  $Z =$  pale reddish. Found in pegmatite at Wodgina, Western Australia, and Varuträsk, Sweden.

**Graftonite**  $[(Fe,Mn,Ca)_3(PO_4)_2]$  is monoclinic<sup>41a</sup> with  $a:b:c = 0.766:1:0.533$ ,  $\beta = 99^\circ 12'$ . Crystals may be interlaminated with triphylite.  $H. = 5$ .  $G. = 3.67-3.79$ .  $F. = 2$ . Soluble in HCl.  $X = b$ .  $Z \wedge c = 36^\circ$ ,  $r < v$ . Dispersion of extinction position.  $(+)2V = 55^\circ-68^\circ$ ,  $r > v$ , distinct.  $N_X = 1.700$ ,  $N_Y = 1.705$ ,  $N_Z = 1.724$ ,  $N_Z - N_X = 0.024$ . Again:<sup>42</sup>  $N_X = 1.709$ ,  $N_Y = 1.714$ ,  $N_Z = 1.733$ ,  $N_Z - N_X = 0.024$ . Color salmon pink, darkening on exposure; colorless in section, or  $X$  and  $Y =$  colorless,  $Z =$  pink. Found in pegmatite in Grafton County, New Hampshire, and at Greenwood, Maine.

**Fillowite**  $[(Mn,Fe,Ca,HNa)_3P_2O_8]$  is monoclinic with  $a:b:c = 1.730:1:1.109$ ,  $\beta = 121^\circ 29'$ . Crystals pseudorhombohedral, with distinct 001 cleavage.  $H. = 4.5$ .  $G. = 3.43$ .  $F. = 1.5$ . Soluble in acid.  $(+)2V =$  small,  $r < v$ .  $N_X = 1.672$ ,  $N_Y = 1.672$ ,  $N_Z = 1.676$ ,  $N_Z - N_X = 0.004$ . Color yellow, reddish brown, colorless. Found in pegmatite at Branchville, Connecticut.

**Gamagarite**<sup>43</sup>  $[Ba_4(Fe,Mn)_2(VO_4)_4 \cdot (H_2O?)]$  is monoclinic with  $c/a = 1.15$ ,  $\beta = 117^\circ 20'$ . Crystals elongated along  $b$ . Poor 001 and 100 cleavages.  $H. = 4.5-5$ .  $G. = 4.62$ .  $X \wedge c = +41^\circ$  ca.,  $Y = b$ .  $(+)2V = 46^\circ-62^\circ$ ,  $r < v$  distinct.  $N_X = 2.016$ ,  $N_Y = 2.040$ ,  $N_Z = 2.130$ ,  $N_Z - N_X = 0.114$ . Color dark brown with  $X =$  red-brown,  $Y =$  very deep red-brown,  $Z =$  light salmon buff. Found in manganese ore near Postmasburg, South Africa.

**Brackebuschite**  $[(Pb,Mn,Fe)_3(VO_4)_2?]$  is monoclinic;<sup>43a</sup> with  $a:b:c = 1.448:1:1.248$ ,  $\beta = 111^\circ 47'$ .  $a$  8.92,  $b$  6.16,  $c$  7.69 Å. Crystals prismatic.  $G. = 6.05$ .  $(+)2V =$  large,  $r > v$  rather strong.  $N_X = 2.28$  Li,  $N_Y = 2.36$ ,  $N_Z = 2.48$ ,  $N_Z - N_X = 0.020$ . Color black with strong pleochroism:  $X =$  nearly colorless,  $Y =$  clouded reddish brown,  $Z =$  clear reddish brown. Found in ore deposits, in Cordoba, Argentina.

**Arrojadite**<sup>43b</sup>  $\{(Na,K,Ca)_2(Fe,Mn)_5(PO_4)_4\}$  is monoclinic with  $a:b:c = 1.656:1:2.389$ ,  $\beta = 93^\circ 37'$ . Space group  $C_2/m?$ ,  $a$  16.60,  $b$  10.02,  $c$  23.99 Å. U.C. 12. Often an alteration product of triphylite. Good 001 cleavage.  $G. = 3.55$ .  $X = b$ .  $Z \wedge a$

<sup>40</sup> B. Mason: *Geol. För. Förh.*, LXIII, 117 (1941).

<sup>41</sup> C. O. Björling and A. Westgren: *Geol. För. Förh.*, LX, 67 (1938).

<sup>41a</sup> M. L. Lindberg: *Am. Mineral.*, XXXV, 59 (1950).

<sup>42</sup> J. J. Glass and J. J. Fahey: *Am. Mineral.*, XXII, 1035 (1937); M. L. Lindberg (*Bull. Geol. Soc. Am.*, LIX, 1336, 1948) gives  $N_X = 1.713$ ,  $N_Y = 1.719$ ,  $N_Z = 1.739$ ,  $N_Z - N_X = 0.026$ .

<sup>43</sup> J. E. de Villiers: *Am. Mineral.*, XXVIII, 329 (1943).

<sup>43a</sup> L. G. Berry and A. R. Graham: *Am. Mineral.*, XXXIII, 489 (1948).

<sup>43b</sup> M. L. Lindberg: *Am. Mineral.*, XXXV, 59 (1950).



= 18°. (-)2V = 80° to 70°,  $r < v$ .  $N_X = 1.649$ ,  $N_Y = 1.654$ ,  $N_Z = 1.657$ ,  $N_Z - N_X = 0.008$ . Again:  $N_X = 1.664$ ,  $N_Y = 1.670$ ,  $N_Z = 1.675$ ,  $N_Z - N_X = 0.011$ . Colorless except in thick plates which have X = colorless, Y = pale green, Z = pale yellow-green. Found in pegmatite in South Dakota and Brazil.

### (a) WITHOUT ADDITIONAL ANIONS—HYDROUS

**Reddingite** [(Mn,Fe)<sub>3</sub>(PO<sub>4</sub>)<sub>2</sub>·3H<sub>2</sub>O] is orthorhombic dipyramidal <sup>44</sup> with  $a:b:c = 0.943:1:0.862$ . Space group <sup>44</sup> *Pmna*;  $a$  9.52,  $b$  10.06,  $c$  8.70 Å. U.C. 4. Crystals pyramidal with poor 010 cleavage. H. = 3–3.5. G. = 3.2. F. = 2.5–3. Soluble in acid. Y =  $b$ ; Z =  $a$ . With 2.19 FeO:  $N_X = 1.643$ ,  $N_Y = 1.648$ ,  $N_Z = 1.674$ ,  $N_Z - N_X = 0.029$ . With <sup>46</sup> 12.68 FeO: (+)2V = 65°,  $r > v$ .  $N_X = 1.655$ ,  $N_Y = 1.662$ ,  $N_Z = 1.683$ ,  $N_Z - N_X = 0.028$ . Color pink, violet, red-brown, with X = colorless, Y = pinkish brown, Z = pale yellow. Found in pegmatite, as at Branchville, Connecticut.

**Hopeite** <sup>44</sup> [Zn<sub>3</sub>(PO<sub>4</sub>)<sub>2</sub>·4H<sub>2</sub>O] is orthorhombic dipyramidal with  $a:b:c = 0.576:1:0.274$ . Space group *Pnma*;  $a$  10.64,  $b$  18.32,  $c$  5.03 Å. U.C. 4. Crystals prismatic with perfect 010, distinct 100, and poor 001 cleavages. H. = 2.5–3. G. = 3.04. F. = 5. Soluble in acid. Optically there are two types, commonly intergrown, called  $\alpha$ - and  $\beta$ -hopeite. The former has slightly higher density than the latter. In the former X =  $a$ , Y =  $c$ , (-)2V = 36°,  $r < v$  weak,  $N_X = 1.572$ ,  $N_Y = 1.591$ ,  $N_Z = 1.592+$ ,  $N_Z - N_X = 0.02+$ . In the latter X =  $a$ , Y =  $b$  or  $c$ , (-)2V = 0°±, dispersion weak,  $N_X = 1.574$ ,  $N_Y = 1.582$ ,  $N_Z = 1.582$ –1.59,  $N_Z - N_X = 0.008+$ . Again: <sup>44</sup> (-)2V = 37°,  $N_X = 1.589$ ,  $N_Y = 1.598$ ,  $N_Z = 1.599$ ,  $N_Z - N_X = 0.010$ . Both types are grayish. When warmed,  $\alpha$ -hopeite is destroyed at 105° C., while  $\beta$ -hopeite becomes opaque only at 129° C. Found in zinc mines at Altenberg and at Broken Hill, Rhodesia.

**Salmonsite** [Mn<sub>9</sub>Fe<sub>2</sub>(PO<sub>4</sub>)<sub>8</sub>·14H<sub>2</sub>O?] is orthorhombic with two distinct cleavages at right angles. H. = 4. G. = 2.88. Z parallel to fibers. (+)2V = very large,  $r < v$  strong.  $N_X = 1.655$ ,  $N_Y = 1.66$ ,  $N_Z = 1.670$ ,  $N_Z - N_X = 0.015$ . Color buff with X = colorless, Y = yellow, Z = orange-yellow. Found in pegmatite at Pala, California.

**Trichalcite** (Cu<sub>3</sub>As<sub>2</sub>O<sub>8</sub>·5H<sub>2</sub>O?) is orthorhombic <sup>46</sup> with  $a:b:c = 0.384:1:0.207$ ;  $a$  10.34,  $b$  26.9,  $c$  5.57 Å. Pseudohexagonal by twinning on 101. Crystals platy. H. = 2.5. F. = 2. Easily soluble in HCl. X normal to plates, Y parallel to their length. (-)2V = large.  $N_X = 1.67$ ,  $N_Y = 1.686$ ,  $N_Z = 1.698$ ,  $N_Z - N_X = 0.028±$ . Color verdigris-green; in section pale bluish green, not pleochroic. Found on tetrahedrite at Turginsk, U. S. S. R.

**Brandtite** [Ca<sub>2</sub>Mn(AsO<sub>4</sub>)<sub>2</sub>·2H<sub>2</sub>O] is monoclinic prismatic <sup>44,46</sup> with  $a:b:c = 0.441:1:0.441$ ,  $\beta = 99^\circ 30'$ . Space group *P2<sub>1</sub>/c*;  $a$  5.65,  $b$  12.80,  $c$  5.65 Å. U.C. 2. Crystals prismatic with distinct 010 cleavage. Twinning common on 100. H. = 3.5. G. = 3.67. F. = 2.5–3. Soluble in HCl. X =  $b$ ; Y  $\wedge$   $c = -6^\circ$  to  $-8^\circ$ . (+)2V = 23°,  $r < v$  rather strong.  $N_X = 1.709$ ,  $N_Y = 1.711$ ,  $N_Z = 1.724$ ,  $N_Z - N_X = 0.015$  (Larsen <sup>47</sup>);  $N_X = 1.707$ ,  $N_Y = ?$ ,  $N_Z = 1.729$ ,  $N_Z - N_X = 0.02$  (Aminoff <sup>47</sup>). Colorless. Found at the Harstig mine in Sweden.

<sup>44</sup> C. W. Wolfe: *Am. Mineral.*, XXV, 738 and 787 (1940).

<sup>45</sup> H. Berman and F. A. Gonyer: *Am. Mineral.*, XV, 375 (1930).

<sup>46</sup> T. Geiger: *Schw. Min. Pet. Mit.*, XXVIII, 468 (1948).

<sup>47</sup> G. Aminoff: *Geol. För. Förh.*, XLI, 161 (1919).



**Roselite**  $[Ca_2(Co,Mg)(AsO_4)_2 \cdot 2H_2O]$  is monoclinic prismatic<sup>48</sup> with  $a:b:c$ <sup>49</sup> = 0.437:1:0.437,  $\beta = 100^\circ 53'$ . Space group  $P2_1/c$ ;  $a$  5.60,  $b$  12.80,  $c$  5.60 Å. U.C. 2. Crystals small, complex, with complicated lamellar twinning and perfect 010 cleavage.  $H. = 3.5$ .  $G. = 3.5-3.7$ .  $F. = 3$ . Soluble in acid. For pink crystals<sup>48</sup> the optic plane is 010;  $X \wedge a = 0^\circ-1^\circ$ .  $(+)2V = 75^\circ$ ,  $r < v$  strong.  $N_X = 1.694$ ,  $N_Y = 1.704$ ,  $N_Z = 1.719$ ,  $N_Z - N_X = 0.025$ . For dark rose crystals<sup>48</sup> (doubtless with more cobalt)  $X = b$ ,  $Y \wedge a = +12^\circ$  to  $+20^\circ$ .  $(+)2V = 60^\circ$ ,  $r < v$ .  $N_X = 1.725$ ,  $N_Y = 1.728$ ,  $N_Z = 1.735$ ,  $N_Z - N_X = 0.010$ . Color pink to red; in thin section colorless or pleochroic with  $X =$  deep rose-red,  $Y =$  pale rose,  $Z =$  nearly colorless. Zonal growth common. Found in ores at Schneeberg, Saxony.

**Collinsite**<sup>44</sup>  $[Ca_2(Mg,Fe)(PO_4)_2 \cdot 2H_2O]$  is triclinic pinacoidal with  $a:b:c = 0.848:1:0.800$ ,  $\alpha = 96^\circ 48'$ ,  $\beta = 107^\circ 16'$ ,  $\gamma = 104^\circ 32'$ . Space group  $P\bar{1}$ ;  $a$  5.70,  $b$  6.72,  $c$  5.38 Å. U.C. 1. Bladed crystals with 001 and 010 cleavages.  $H. = 3.5$ .  $G. = 2.99$ .  $F. =$  easy. Soluble in acid.  $X$ <sup>49</sup> at  $\phi = -50^\circ 30'$ ,  $\rho = 50^\circ$ ;  $Y$  at  $\phi = -173^\circ 30'$ ,  $\rho = 58^\circ$ ;  $Z$  at  $\phi = 72^\circ 30'$ ,  $\rho = 58^\circ$ .  $(+)2V = 80^\circ$ ,  $N_X = 1.632$ ,  $N_Y = 1.642$ ,  $N_Z = 1.657$ ,  $N_Z - N_X = 0.025$ . Color in mass light brown, with silky luster. Forms concentric layers in phosphorite nodules at François Lake, British Columbia.

**Fairfieldite**<sup>44</sup>  $[Ca_2(Mn,Fe)(PO_4)_2 \cdot 2H_2O]$  is triclinic pinacoidal with  $a:b:c = 0.879:1:0.833$ ,  $\alpha = 102^\circ 5'$ ,  $\beta = 108^\circ 42'$ ,  $\gamma = 90^\circ 5'$ . Space group  $P\bar{1}$ ;  $a$  5.77,  $b$  6.56,  $c$  5.47 Å. U.C. 1. Crystals equant, with perfect 001 and distinct 010 cleavages.  $H. = 3.5$ .  $G. = 3.08$ .  $F. = 4$ . Soluble in acid.  $X$  at  $\phi = 120^\circ$ ,  $\rho = 60^\circ$ ;  $Y$  at  $\phi = -102^\circ$ ,  $\rho = 36^\circ$ ;  $Z$  at  $\phi = 18^\circ$ ,  $\rho = 69^\circ$ . With<sup>50</sup> only 1.0% FeO:  $(+)2V =$  large,  $N_X = 1.633$ ,  $N_Y = 1.641$ ,  $N_Z = 1.652$ ,  $N_Z - N_X = 0.019$ . With<sup>45</sup> 4.75 FeO:  $(+)2V = 86^\circ$ ,  $r > v$ ;  $N_X = 1.640$ ,  $N_Y = 1.650$ ,  $N_Z = 1.660$ ,  $N_Z - N_X = 0.020$ . Colorless in section. Found in pegmatite at Branchville, Connecticut, and at Rabenstein, Bavaria.

**Uzbekite**<sup>51</sup>  $[Cu_3(VO_4)_2 \cdot 3H_2O]$  is biaxial and negative. Acicular crystals in platy masses.  $(-)2V =$  large,  $r < v$  strong.  $N_X = 2.01$ ,  $N_Y = 2.04$ ,  $N_Z = 2.07$ ,  $N_Z - N_X = 0.06$ . Weakly pleochroic in green. Found in Fergana, U. S. S. R.

**Phosphophyllite**<sup>44</sup>  $[Zn_2(Fe,Mn)(PO_4)_2 \cdot 4H_2O]$  is monoclinic prismatic with  $a:b:c = 2.026:1:2.079$ ,  $\beta = 120^\circ 15'$ . Space group  $P2_1/c$ ;  $a$  10.23,  $b$  5.08,  $c$  10.49 Å. U.C. 2. Crystals tabular with perfect 100 and distinct 010 and  $\bar{1}02$  cleavages.  $H. = 3-4$ .  $G. = 3.13$ . Lamellar 100 twinning.  $Z = b$ ;  $Y \wedge a = 50^\circ$ .  $(-)2V = 50^\circ \pm$ ,  $N_X = 1.595$ ,  $N_Y = 1.614$ ,  $N_Z = 1.616$ ,  $N_Z - N_X = 0.021$ . Colorless or pale blue or green. An alteration product in pegmatite at Pleystein, Bavaria.

**Picropharmacolite**  $[Ca_2Mg(AsO_4)_2 \cdot 6H_2O]$  is monoclinic with perfect 010 and 100 cleavages. Foliated aggregates. Soft.  $G. = 2.58$ .  $Y = b$ ;  $X \wedge c = 37^\circ$ .  $(+)2V = 40^\circ$ ,  $r < v$  distinct.  $N_X = 1.631$ ,  $N_Y = 1.632$ ,  $N_Z = 1.640$ ,  $N_Z - N_X = 0.009$ . Found on dolomite, as at Joplin, Missouri.

**Huegelite**<sup>52</sup>  $[(Pb,Zn)_3V_2O_8 \cdot 8H_2O?]$  is monoclinic with  $a:b:c = 0.489:1:0.384$ ,  $\beta = 119^\circ 48'$ . Crystals {010} laths.  $G. = 5$ .  $X \wedge c =$  small (red);  $Y \wedge c =$  small (blue);  $Z = b$ .  $(+)2V =$  small (red),  $0^\circ$  (red-orange), large (blue).  $N_Y$

<sup>48</sup> M. A. Peacock: *Am. Mineral.*, XXI, 589 (1936).

<sup>49</sup> Reported with reference to certain unconfirmed cleavages as pole face and origin of azimuths. Probably (see ref. 44) subject to revision.

<sup>50</sup> K. K. Landes: *Am. Mineral.*, X, 355 (1925).

<sup>51</sup> T. Barth and H. Berman: *Chem. Erde*, V, 22 (1930).

<sup>52</sup> V. Dürrfeld: *Zeit. Krist.*, LI, 278 (1913); LIII, 182 (1914). Formula quite uncertain.

= 1.915,  $N_z - N_x$  = rather weak. Color yellow, orange, brown, with X = very pale greenish yellow, Y = pale orange, Z = ? 010 plates show sharp parallel extinction in white light with abnormal green interference colors. Found on galena at Reichenbach, Baden.

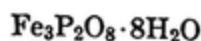
### VIVIANITE GROUP

The vivianite group consists of monoclinic phosphates and arsenates of iron, magnesium, cobalt, nickel, and zinc with eight molecules of water. The following types are recognized:

		$a:b:c$	$\beta$
Vivianite	$\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$	0.750:1:0.350	$104^\circ 18'$
Erythrite	$\text{Co}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$	0.763:1:0.355	$105^\circ 2'$
Annabergite	$\text{Ni}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$	0.762:1:0.354	$105^\circ 45'$
Koettigite	$\text{Zn}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$	0.759:1:0.353	$103^\circ 50'$
Hoernesite	$\text{Mg}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$	0.768:1:0.359	$104^\circ 25'$
Bobierite	$\text{Mg}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$	0.360:1:0.167	$104^\circ 1'$

### VIVIANITE<sup>53</sup>

#### MONOCLINIC PRISMATIC



$$a:b:c = 0.750:1:0.350 \quad \beta = 104^\circ 18'$$

COMP. Usually nearly pure, but the iron may be partly oxidized; rarely, it may be replaced (in part or wholly?) by Mg, etc.

STRUC. Space group  $C2/m$ ;  $a$  10.039,  $b$  13.388,  $c$  4.687 Å. U.C. 2.

PHYS. CHAR. Crystals prismatic or {100} tablets with perfect 010 and distinct 100 cleavages. Flexible. H. = 2. G. = 2.71. F. = 1.5. Soluble in HCl.

OPT. PROP. The optic plane and X are normal to 010;  $Z \wedge c = -28.5^\circ$ . (+)2V = large. See Fig. 108. Slight horizontal dispersion, with  $r < v$ . The optic properties change with exposure to air. Fresh vivianite is colorless, but it changes gradually to green, then blue, and finally brown, as the iron is oxidized. When the mineral is powdered the change to blue is almost instantaneous, followed in a short time by the change to brown. The indices change at the same time, as follows:

Color	$N_x$	$N_y$	$N_z$	$N_z - N_x$	2V <sub>z</sub>	Pleochroism	Authority
Pale green	1.580	1.598	1.627	0.047	Large	None	Larsen <sup>27</sup>
Deep blue	1.579	1.603	1.633	0.054	$85^\circ \pm$	Strong	Larsen <sup>27</sup>
Pleochroic	1.570	1.600	1.636	0.066	?	Strong	Polyanin <sup>54</sup>
Deep green	Indices higher			Lower	$90^\circ +$	Strong	Ulrich <sup>55</sup>

Blue vivianite is pleochroic with X = deep blue, Y = nearly colorless, Z = pale olive green or brownish.

A scratch with a hard pencil point suffices to orient a plate of vivianite which is parallel to the perfect 010 cleavage (or the 110 face); in fact, a mark normal to  $c$

<sup>53</sup> T. Barth: *Am. Mineral.*, XXII, 325 (1937).

<sup>54</sup> V. A. Polyanin: *Min. Abst.*, VII, 440 (1940).

<sup>55</sup> F. Ulrich: *Min. Abst.*, II, 141 (1923) and III, 49 (1926); *Zeit. Krist.*, LXIV, 143 (1926).

produces no scratch, whereas one in any other direction produces short cracks across the scratch *nearly normal to c*. Such plates may be elongated parallel to *c* or to  $\bar{1}11$ .

**ALTER.** Vivianite changes very easily and rapidly by oxidation of the iron, as noted.

**OCCUR.** It is found as a secondary mineral in metalliferous veins; also known in clay beds; also with limonite; in cavities in bones.

**DIAG.** The deep blue color, the optic properties, and the flexibility of the crystals are characteristic.

**Erythrite** ( $Co_3As_2O_8 \cdot 8H_2O$ ) is monoclinic prismatic<sup>44</sup> with  $a:b:c = 0.763:1:0.355$ ,  $\beta = 105^\circ 2'$ . Space group  $C2/m$ ;  $a$  10.184,  $b$  13.34,  $c$  4.73 Å. U.C. 2. Crystals prismatic, vertically striated, or {010} tablets, with perfect 010 and poor 100 and  $\bar{1}01$  cleavages. Cleavage flakes flexible normal to *c*.  $H. = 1.5-2.5$ .  $G. = 3.09$ .  $F. = 2$ . Soluble in HCl to a rose-red solution. The optic plane and *X* are normal to 010;  $Z \wedge c = -32^\circ$ .  $(\pm)2V = 89^\circ$  *ca.*  $r > v$ , with slight crossed dispersion.  $N_X = 1.626$ ,  $N_Y = 1.662$ ,  $N_Z = 1.699$ ,  $N_Z - N_X = 0.073$  Na. Color crimson to gray with *X* = pale pinkish, *Y* = pale violet, *Z* = red and  $Y < X < Z$ ; colors vary. Streak pale red, dry powder lavender blue. *Lavendulan* is probably a cuprian variety of erythrite; it has  $N_X = ?$ ,  $N_Y = 1.715$ ,  $N_Z = 1.725$ , and inclined extinction. Erythrite is formed by the oxidation of cobalt ores. The pink color and optic properties of cleavage flakes are characteristic.

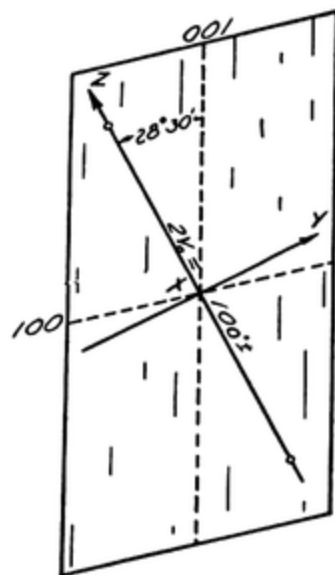


FIG. 108. The optic orientation of vivianite.

**Annabergite**<sup>44</sup> ( $Ni_3As_2O_8 \cdot 8H_2O$ ) is monoclinic prismatic with  $a:b:c = 0.762:1:0.354$ ,  $\beta = 104^\circ 45'$ . Space group  $C2/m$ ;  $a$  10.12,  $b$  13.28,  $c$  4.70 Å. U.C. 2. Crystals fibrous or {010} tablets with perfect 010 cleavage.  $H. = 2.5$ .  $G. = 3.07$ .  $F. = 4$ . Soluble in HCl.  $X = b$ ;  $Z \wedge c = +35^\circ$ .  $(-)2V = 84^\circ$ ,  $r > v$  rather strong with distinct crossed dispersion.  $N_X = 1.622$ ,  $N_Y = 1.658$ ,  $N_Z = 1.687$ ,  $N_Z - N_X = 0.065$ . A crystal with 17.23 NiO, 11.97 CoO, 8.54 ZnO, 34.63  $As_2O_5$ , 22.55  $H_2O$ , 0.83  $Fe_2O_3$  has  $Z \wedge c = 37^\circ$  (Rossetti<sup>56</sup>). Color apple green; colorless or weakly pleochroic in green tints in thin section. Formed by oxidation of nickel ores, as at Chatham, Connecticut. *Cabrerite* is a variety said to contain Mg.

**Koettigite**<sup>44</sup> ( $Zn_3As_2O_8 \cdot 8H_2O$ ) is monoclinic prismatic with  $a:b:c = 0.759:1:0.353$ ,  $\beta = 104^\circ 30'$ . Space group  $C2/m$ ;  $a$  10.11,  $b$  13.31,  $c$  4.70 Å. U.C. 2. Crystals vertical fibers, with perfect 010 cleavage.  $H. = 2.5-3$ .  $G. = 3.33$ .  $F. = 3?$  Soluble in acid.  $X = b$ ;  $Z \wedge c = -37^\circ$ .  $(+)2V = 74^\circ$ ,  $r < v$  rather strong. Extinction imperfect on 010 on account of horizontal dispersion.  $N_X = 1.662$ ,  $N_Y = 1.683$ ,  $N_Z = 1.717$ ,  $N_Z - N_X = 0.055$ . Wolfe<sup>44</sup> gives:  $N_X = 1.622$ ,  $N_Y = 1.638$ ,  $N_Z = 1.671$ ,  $N_Z - N_X = 0.049$ . Color carmine or brownish. Pink in section and not pleochroic. Found with smaltite at Schneeberg, Saxony.

**Hoernesite**<sup>44</sup> ( $Mg_3As_2O_8 \cdot 8H_2O$ ) is monoclinic with  $a:b:c = 0.768:1:0.359$ ,  $\beta = 104^\circ 25'$ . Crystals {010} tablets or prismatic, with 010 cleavage.  $H. = 1$ .  $G. = 2.7$ .  $F. =$  easy. Soluble in acid.  $X = b$ ;  $Z \wedge c = -32^\circ$ .  $(+)2V = 60^\circ$ ,  $r < v$ .  $N_X = 1.563$ ,  $N_Y = 1.571$ ,  $N_Z = 1.596$ ,  $N_Z - N_X = 0.033$ . Colorless. Found in calcite in Hungary.

<sup>56</sup> V. Rossetti: *Per. Min. Roma*, XIII, 201 (1942); *Min. Abst.*, IX, 216 (1946).

**Bobierite**<sup>44</sup> ( $\text{Mg}_3\text{P}_2\text{O}_8 \cdot 8\text{H}_2\text{O}$ ) is monoclinic prismatic with  $a:b:c = 0.360:1:0.167$ ,  $\beta = 104^\circ 1'$ . Space group  $P2_1/c$ ;  $a$  9.946,  $b$  27.654,  $c$  4.639 Å. U.C. 4. Crystals acicular with distinct 010 cleavage.  $H. = 2$ .  $G. = 2.17$ . Fusible. Soluble in acid.  $Y = b$ ;  $Z \wedge c = -30^\circ$ .  $(+ )2V = 71^\circ$ ,  $r < v$  weak.  $N_X = 1.510$ ,  $N_Y = 1.520$ ,  $N_Z = 1.543$ ,  $N_Z - N_X = 0.033$ . Colorless. Found in guano. An enterolith found in New Zealand<sup>47</sup> is an iron-rich bobierite with properties  $\{ (+ )2V = 55^\circ\text{--}60^\circ$ ,  $N_X = 1.547$ ,  $N_Y = 1.553$ ,  $N_Z = 1.582$ ,  $N_Z - N_X = 0.035$ ;  $Z \wedge c = 28^\circ\text{--}30^\circ \}$  intermediate between those of vivianite and those of bobierite,

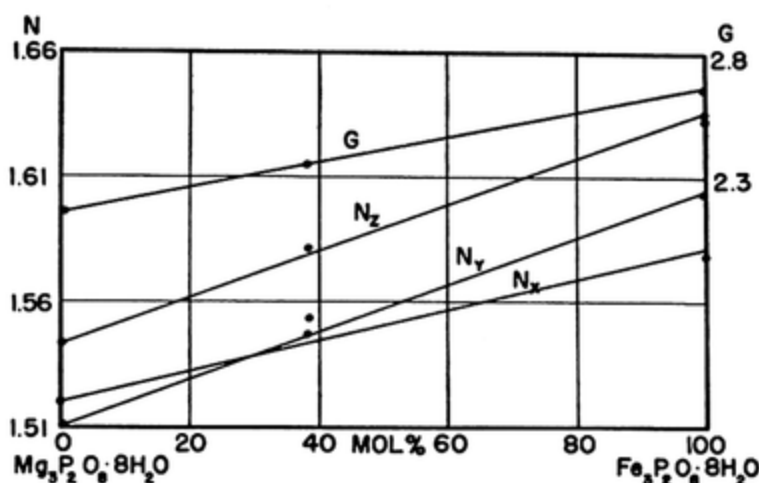


FIG. 109. Properties of the vivianite-bobierite series.

as shown in Fig. 109. That such a series is complete seems very doubtful since the end-members differ in crystal structure (different space groups).

**Symplesite**<sup>44</sup> ( $\text{Fe}_3\text{As}_2\text{O}_8 \cdot 8\text{H}_2\text{O}$ ) is triclinic pinacoidal<sup>48</sup> with  $a:b:c = 0.832:1:0.503$ ,  $\alpha = 99^\circ 55'$ ,  $\beta = 97^\circ 22'$ ,  $\gamma = 105^\circ 57'$ . Space group  $P\bar{1}$ ;  $a$  7.85,  $b$  9.39,  $c$  4.71 Å. U.C. 1. Crystals prismatic or  $\{1\bar{1}0\}$  tablets with perfect  $1\bar{1}0$  cleavage.  $H. = 2.5$ .  $G. = 3.01$ .  $F. = 7$ . Attacked by  $\text{HCl}$ .  $X \perp 1\bar{1}0$ ;  $Z \wedge c$ <sup>49</sup>  $= 32^\circ$ .  $(- )2V = 87^\circ$ ,  $r > v$  rather strong.  $N_X = 1.635$ ,  $N_Y = 1.668$ ,  $N_Z = 1.702$ ,  $N_Z - N_X = 0.067$ . Color pale indigo or green and pleochroic with  $X =$  light bluish green to deep blue,  $Y =$  colorless to pale greenish yellow,  $Z =$  yellowish to yellowish green. Found with siderite or pharmacolite, as at Pisek, Bohemia.

**Ferri-symplesite**<sup>49</sup> [ $\text{Fe}_6(\text{OH})_6(\text{AsO}_4)_4 \cdot 13\text{H}_2\text{O}$ ?] is fibrous with  $G. = 2.89$ .  $N = 1.65$  ca.,  $N_Z - N_X =$  strong. Color deep amber brown, slightly pleochroic. An oxidation product from symplesite.

<sup>47</sup> C. O. Hutton: *N. Zealand Jour. Sci. Tech.*, XXIII, 9B (1941).

<sup>48</sup> Optically symplesite seems to be monoclinic with  $X$  normal to  $010$  ( $= 1\bar{1}0$  of triclinic setting) and  $Z \wedge c = -32^\circ$ . But varieties with darker pleochroism have  $Z \wedge c$  from  $37^\circ$  to  $51^\circ$ , as follows (*Zeit. Krist.*, LXXXVIII, 176, 1934):

$X =$ Dark blue-green	Green (brownish)	Brown (greenish)
$Y =$ Greenish brown	Brown	Brown
$Z =$ Dark brown	Dark brown	Brown
$Z \wedge c =$ $37^\circ\text{--}38^\circ$	$42^\circ$	$45^\circ\text{--}51^\circ$

<sup>49</sup> T. L. Walker and A. L. Parsons: *U. Toronto Geol. Studies*, XVII, 16 (1924).

**Vashegyite**  $[Al_8(OH)_6(PO_4)_6 \cdot 27H_2O?]$  is fibrous.  $H. = 2.5$ .  $G. = 1.96$ .  $F. = 7$ . Soluble in acid. Positive elongation.  $N = 1.48$ .  $N_Z - N_X = 0.02$ . Also isotropic <sup>60</sup> with  $N = 1.49-1.505$ . Colorless. Found in iron ore deposits at Vashegy, Hungary.

**Picite**  $[Fe'''_6(OH)_6(PO_4)_4 \cdot 7H_2O?]$  is apparently amorphous.  $H. = 3-4$ .  $G. = 2.83$ . Isotropic <sup>61</sup> with  $N = 1.64$ . Color dark brown; streak yellow. Found in Bohemia.

**Parahopeite** <sup>44</sup>  $[Zn_3(PO_4)_2 \cdot 4H_2O]$  is triclinic pinacoidal with  $a:b:c = 0.764:1:0.702$ ,  $\alpha = 93^\circ 17'$ ,  $\beta = 91^\circ 55'$ ,  $\gamma = 91^\circ 19'$ . Space group  $P\bar{1}$ ;  $a$  5.755,  $b$  7.535,  $c$  5.292 Å. U.C. 1. Crystals {100} tablets with good 010 cleavage. Lamellar twinning on 100 common.  $H. = 3.5-4$ .  $G. = 3.307$ .  $F. = \text{easy}$ . Soluble in HCl.  $X$  is near  $a$ ; extinction on 100 is  $Y' \wedge c = 30^\circ$ ; on 010 extinction is at  $0^\circ$  to  $25^\circ$ .  $(+)2V = \text{nearly } 90^\circ$ ,  $r < v$ .  $N_X = 1.614$ ,  $N_Y = 1.625$ ,  $N_Z = 1.637$ ,  $N_Z - N_X = 0.023$ . Stable to  $163^\circ C$ . Colorless. Found in zinc ore at Broken Hill, Rhodesia.

**Stewartite** <sup>44</sup>  $[Mn_3(PO_4)_2 \cdot 4H_2O?]$  is triclinic in {100} tablets with distinct 010 cleavage.  $G. = 2.94$ . Axis  $X$  is nearly normal to 100; extinction on 010 is  $X' \wedge c = 56^\circ$ ; 010 plate shows an optic axis in the field.  $(-)2V = \text{very large}$  with strong dispersion.  $N_X = 1.63$ ,  $N_Y = 1.66$ ,  $N_Z = 1.69$ ,  $N_Z - N_X = 0.06$ . Color yellow, with  $X = \text{colorless}$ ,  $Y = \text{very pale yellow}$ ,  $Z = \text{yellow}$ . An alteration product of lithiophyllite at the Stewart mine, Pala, California.

**Anapaite** <sup>44</sup>  $[Ca_2Fe(PO_4)_2 \cdot 4H_2O]$  is triclinic pinacoidal with  $a:b:c = 0.932:1:0.851$ ,  $\alpha = 101^\circ 34'$ ,  $\beta = 104^\circ 5'$ ,  $\gamma = 71^\circ 3'$ . Space group  $P\bar{1}$ ;  $a$  6.41,  $b$  6.88,  $c$  5.86 Å. U.C. 1. Crystals vertical fibers with perfect 001 and distinct 010 cleavages.  $H. = 3.5$ .  $G. = 2.81$ . Soluble in cold acid.  $X$  is at  $\phi = -119^\circ$ ,  $\rho = 81^\circ$ ;  $Y$  is at  $\phi = 147^\circ$ ,  $\rho = 70^\circ$ ;  $Z$  is at  $\phi = -6^\circ$ ,  $\rho = 21^\circ$ . Extinction on 100 is at  $15^\circ$  to  $c$ . Some plates are nearly normal to  $Z$ .  $(+)2V = 53^\circ$ ,  $r > v$ .  $N_X = 1.602$ ,  $N_Y = 1.613$ ,  $N_Z = 1.649$ ,  $N_Z - N_X = 0.047$ . Color greenish white. Found in limonite mines near Anapa, Kuban, U. S. S. R.

## (b) WITH ADDITIONAL ANIONS—ANHYDROUS

### APATITE GROUP

The minerals of the apatite group are hexagonal phosphates, arsenates, or vanadates <sup>62</sup> of calcium or lead with a small amount of fluorine, chlorine, or hydroxyl (or even oxygen, carbonate, or sulfate). The space group for all members is  $C6_3/m$  with U.C. 2. Apatite is the only mineral of the group found commonly in rocks; the crystal habit is short prismatic, with basal or pyramidal terminations. The minerals are all negative and normally uniaxial, but several are likely to show

<sup>60</sup> F. Ulrich: *Min. Abst.*, II, 141 (1923); A. Jahn and E. Gruner: *Min. Abst.*, V, 429 (1934).

<sup>61</sup> F. Slavik: *Tables Ann. Intern. Const.*, V (1925).

<sup>62</sup> One silicate-sulfate is included.

biaxial character. The chief species and varieties of this group are the following:

SPECIES      SUBSPECIES  
(AND VARIETIES)

Apatite	Svabite	$3\text{Ca}_3\text{As}_2\text{O}_8 \cdot \text{CaF}_2$	or $\text{Ca}_5\text{FAs}_3\text{O}_{12}$
	Fluorapatite	$3\text{Ca}_3\text{P}_2\text{O}_8 \cdot \text{CaF}_2$	or $\text{Ca}_5\text{FP}_3\text{O}_{12}$
	Chlorapatite	$3\text{Ca}_3\text{P}_2\text{O}_8 \cdot \text{CaCl}_2$	or $\text{Ca}_5\text{ClP}_3\text{O}_{12}$
	Hydroxylapatite	$3\text{Ca}_3\text{P}_2\text{O}_8 \cdot \text{Ca}(\text{OH})_2$	or $\text{Ca}_5\text{OHP}_3\text{O}_{12}$
	Podolite <sup>63</sup> (or carbapatite)	$3\text{Ca}_3\text{P}_2\text{O}_8 \cdot \text{CaCO}_3$	or $\text{Ca}_{10}\text{CO}_3\text{P}_6\text{O}_{24}$
	Ellestadite	$3\text{Ca}_3\text{SiSO}_8 \cdot \text{Ca}(\text{OH})_2$	or $\text{Ca}_{10}(\text{OH})_2\text{Si}_3\text{S}_3\text{O}_{24}$
	Strontianapatite	$3(\text{Ca}, \text{Sr})_3\text{P}_2\text{O}_8 \cdot \text{Ca}(\text{F}, \text{OH})_2$	or $(\text{Ca}, \text{Sr})_5(\text{F}, \text{OH})\text{P}_3\text{O}_{12}$
	Manganianapa- tite	$3(\text{Ca}, \text{Mn})_3\text{P}_2\text{O}_8 \cdot \text{CaF}_2$	or $(\text{Ca}, \text{Mn})_5\text{FP}_3\text{O}_{12}$
	Britholite	$3(\text{Ca}, \text{Ce})_3(\text{Si}, \text{P})_2\text{O}_8 \cdot \text{Ca}(\text{OH})_2$	or $(\text{Ca}, \text{Ce})_5(\text{F}, \text{OH})(\text{Si}, \text{P})_3\text{O}_{12}$
	Abukumalite	$3(\text{Ca}, \text{Y})_3(\text{Si}, \text{P})_2\text{O}_8 \cdot \text{Ca}(\text{OH}, \text{F})_2$	or $(\text{Ca}, \text{Y})_5(\text{F}, \text{OH})(\text{Si}, \text{P})_3\text{O}_{12}$
Pyromorphite	$3\text{Pb}_3\text{P}_2\text{O}_8 \cdot \text{PbCl}_2$	or $\text{Pb}_5\text{ClP}_3\text{O}_{12}$	
Vanadinite	$3\text{Pb}_3\text{V}_2\text{O}_8 \cdot \text{PbCl}_2$	or $\text{Pb}_5\text{ClV}_3\text{O}_{12}$	
Mimetite	$3\text{Pb}_3\text{As}_2\text{O}_8 \cdot \text{PbCl}_2$	or $\text{Pb}_5\text{ClAs}_3\text{O}_{12}$	

*Dahllite* is intermediate between hydroxylapatite and podolite; *francolite* is between fluorapatite and podolite; *wilkeite* is between hydroxylapatite and ellestadite; *endlichite* is between vanadinite and mimetite; *hedyphane* is between mimetite and apatite; *fermorite* is between hydroxyl-fluorapatite and svabite and contains some strontium; *collophane* is (cryptocrystalline) carbonate-hydroxyl-fluorine-apatite;<sup>64</sup> it is optically isotropic<sup>65</sup> with  $N = 1.57-1.63$ . In *dehrnite* and *lewistonite* part of the calcium is replaced by alkalies; *lewistonite*<sup>66</sup> contains much more  $\text{H}_2\text{O}$  than *dehrnite*, but the excess is probably not essential water.

<sup>63</sup> Considered a mixture by J. Thewlis, G. E. Glock, and M. M. Murray: *Trans. Faraday Soc.*, XXXV, 358 (1939).

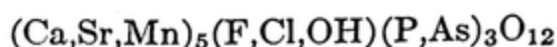
<sup>64</sup> C. Frondel: *Am. Mineral.*, XXVIII, 215 (1943).

<sup>65</sup> Also may be anisotropic with  $(+ )2V = 20^\circ$ ,  $N_x = 1.608$ ,  $N_z = 1.614$ . See *Mineral. Mag.*, XXVIII, 338 (1948).

<sup>66</sup> E. S. Larsen and E. V. Shannon: *Am. Mineral.*, XV, 307 (1930). *Dehrnite* and *lewistonite* were shown to belong to apatite by D. McConnell: *Am. Mineral.*, XXIII, 1 (1938).



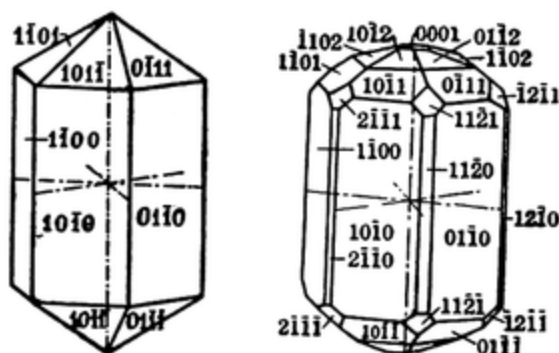
## APATITE



HEXAGONAL DIPYRAMIDAL

$$c/a = 0.73 \pm$$

COMP. Natural apatite is usually near  $Ca_5FP_3O_{12}$  in composition, but it may vary from this in many ways. Not only may the fluorine be replaced by chlorine (especially in meteorites) or hydroxyl, in any proportion, but apparently at least in part by oxygen. Further, the



FIGS. 110, 111. Crystal habits of apatite.

calcium may be replaced in part by manganese or strontium, or, in small part, by sodium, potassium, magnesium, iron, or even carbon.<sup>67</sup> Also, the phosphorus may be replaced by arsenic in any amount (see Fig. 114), or apparently by carbon in small amount.<sup>67</sup> Finally there are more complicated substitutions, such as SiS for PP (see Fig. 115),  $Cr^{+3} + 2Cr^{+6}$  for  $3P^{+5}$  (Minguzzi<sup>68</sup>), and, at least in small amount, Na(Y,Ce, etc.<sup>69</sup>) for CaCa, (Y,Ce, etc.<sup>69</sup>)O for CaF,<sup>70</sup> (Y,Ce, etc.<sup>69</sup>) Si for CaP, NaS for CaP,<sup>71</sup> and perhaps<sup>72</sup>  $Al_3$  for  $Ca_2P$ .

STRUC. Space group  $C6_3/m$ ; for<sup>67</sup>  $Ca_5FP_3O_{12}$   $a$  9.36,  $c$  6.88 Å. U.C. 2.

PHYS. CHAR. Crystals long to short prismatic, terminated by the base or a pyramid; basal cleavage in traces. See Figs. 110 and 111.  $H. = 5$ .  $G. = 3.18$  (for fluorapatite).  $F. = 5$ . Soluble in  $HNO_3$  or  $HCl$ .

OPT. PROP. Negative and commonly strictly uniaxial; rarely biaxial with  $2E$  exceeding  $10^\circ$ . Apatite varies in composition in so many ways that no accurate correlations of optic data with simple variations are

<sup>67</sup> D. McConnell: *Am. Mineral.*, XXIII, 1 (1938).

<sup>68</sup> C. Minguzzi: *Per. Min. Roma*, I, 40 (1941); *Min. Abst.*, IX, 283 (1946).

<sup>69</sup> "Etc." includes the rare-earth elements.

<sup>70</sup> A. Kind: *Chem. Erde*, XII, 50 (1939).

<sup>71</sup> P. Dihn and R. Klement: *Min. Abst.*, IX, 13 (1944).

<sup>72</sup> R. Pieruccini: *Min. Abst.*, X, 261 (1948).

as yet possible. The following correlations are only first approximations (see also Figs. 112-115):

	No	N	NE	No - NE	G.	a	c
Svabite <sup>73</sup>	1.706		1.698	0.008	3.52	(c/a = 0.714)	
Fluorapatite <sup>44, 67</sup>	1.634		1.629	0.005	3.18	9.36	6.88 Å
Chlorapatite <sup>74, 75, 76</sup>	1.667		1.664	0.003	3.20	9.52	6.85 Å
Artificial						9.57	6.74 Å
Hydroxylapatite <sup>67, 75, 76</sup>	1.651		1.644	0.007	3.07	9.425	6.935 Å
Artificial						9.41	6.87 Å
Manganianfluorapatite <sup>67, 77</sup>	1.646		1.641	0.005	3.30	9.33	6.80 Å
Manganianhydroxylapatite <sup>78</sup>	1.661		1.657	0.004	3.19	?	?
Strontianapatite <sup>79</sup>	1.639		1.637	0.002	3.22	?	?
Fermorite <sup>67, 80</sup>	1.660		?	Weak	3.5 ±	9.60	7.00 Å
Francolite <sup>81</sup>	1.629		1.624	0.005	3.15	9.34	6.88 Å
Francolite <sup>82</sup> (-)2V = 0°-36°	1.627-1.630	1.627	1.614-1.617	0.013	3.12	?	?
Dahlite <sup>83</sup>	?	1.619-1.628	?	?	2.93	9.41	6.88 Å
Dahlite <sup>84</sup>	1.603		1.598	0.005	?	9.39	6.88 Å
Podolite <sup>85</sup>	{ 1.630	1.635		0.0075			
			1.622	0.008	3.08	9.32	6.87 Å
Lewistonite <sup>86</sup>	1.621, 1.624		1.611, 1.613	0.010, 0.011	3.08	9.35	6.89 Å
	{ 1.600		1.585	0.015			
Dehrnite <sup>86</sup>	{ 1.623		1.613	0.010	3.04	9.31	6.87 Å
	{ 1.640		1.633	0.007			
Wilkeite <sup>87</sup>	1.640, 1.650		1.636, 1.646	0.004	3.12, 3.16	9.48	6.91 Å
Ellestadite <sup>87</sup>	1.655		1.650	0.005	3.07	9.53	6.91 Å
Britholite <sup>88</sup>	1.777		1.772	0.005	?	9.61	7.02 Å
Abukumalite <sup>89</sup>	1.750		1.752	-0.002	4.35		Similar

<sup>73</sup> A. S. Dadson: *U. Toronto Stud. Geol. Ser.*, XXXV, 51 (1933).

<sup>74</sup> L. Mitchell, G. T. Faust, S. B. Hendricks, and D. S. Reynolds: *Am. Mineral.*, XXVIII, 356 (1943). With 0.16 F. Very similar data given by A. Bianchi: *Atti Soc. Ital. Sci. Nat.*, LVIII, 306 (1919).

<sup>75</sup> S. B. Hendricks, M. E. Jefferson, and V. M. Mosley: *Zeit. Krist.*, LXXXI, 352 (1931).

<sup>76</sup> J. Thewlis, G. E. Glock, and M. M. Murray: *Trans. Faraday Soc.*, XXXV, 358 (1939).

<sup>77</sup> P. Quensel: *Geol. För. Förh.*, LIX, 257 (1937). With 5.32 MnO and 0.26 FeO. G. Pehrman (*Min. Abst.*, VII, 417, 1940) gives a similar report. (No = 1.664, NE = 1.6375, with 4.74 MnO and 0.87 FeO.)

<sup>78</sup> B. Mason: *Geol. För. Förh.*, LXIII, 279 (1941); with 7.50 MnO and 3.07 FeO.

<sup>79</sup> A. Kind: *Chem. Erde*, XII, 50 (1939). With 2.00 SrO.

<sup>80</sup> G. F. H. Smith and G. T. Prior: *Mineral. Mag.*, XVI, 84 (1911).

<sup>81</sup> E. B. Sandell, M. H. Hey, and D. McConnell: *Mineral. Mag.*, XXV, 395 (1939).

<sup>82</sup> J. E. de Villiers: *Am. Jour. Sci.*, CCXL, 443 (1942).

<sup>83</sup> D. McConnell: *Am. Jour. Sci.*, XXXVI, 296 (1938).

<sup>84</sup> H. S. Washington: *Am. Mineral.*, XIV, 369 (1929).

<sup>85</sup> W. Tschirwinsky: *Cent. Min.*, 1907, 279; E. S. Larsen and H. Berman: *U. S. Geol. Surv. Bull.* 848 (1934); see also *Trans. Faraday Soc.*, XXXV, 358 (1939).

<sup>86</sup> E. S. Larsen and E. V. Shannon: *Am. Mineral.*, XV, 307 (1930).

<sup>87</sup> D. McConnell: *Am. Mineral.*, XXII, 977 (1937).

<sup>88</sup> T. Barth and H. Berman: *Chem. Erde*, V, 22 (1930). Also biaxial. *Min. Abst.*, VII, 395 (1939).

<sup>89</sup> S. Hata: *Sci. P. Inst. Chem. Res. Tokyo*, XXXIV, 1018 (1938); *Min. Abst.*, VII, 225 (1939). F. Machatschki: *Naturw.*, XXVII, 161 (1939); *Min. Abst.*, VII, 395 (1939).

Dehrnite and lewistonite are in part biaxial with  $2V$  small or as large as  $40^\circ$ , and an extinction angle of  $12^\circ$ – $16^\circ$ , and perfect basal cleavage.

Color green, blue, red, white, gray, brown. Usually colorless in thin section, but may be gray, blue, or brown with uniform or irregular distribution of color. Heating usually changes the colored types to colorless condition. Colored varieties weakly pleochroic with  $O < E$ ; but in rare cases  $O > E$  is reported. Manganapatite is green or lavender with  $O =$  rich green,  $E =$  bluish green, and  $O < E$ .

**INCL.** Some apatite contains numerous dark inclusions; these may be arranged in vertical lines, or centrally, or in zones. Liquid or gaseous inclusions are also found.

**ALTER.** Apatite is usually quite fresh even when the enclosing minerals have undergone complete alteration.

**OCCUR.** Apatite is widely (sometimes very sparsely) distributed in all kinds of rocks. It occurs most abundantly in regions of crystalline schists, as in Renfrew County, Ontario, and in Odenwald. In Canada it is associated with metamorphosed limestones, and accompanied by titanite, amphibole, zircon, pyroxene, garnet, and vesuvianite. It is found in sedimentary rocks chiefly as the result of organic deposits. In igneous rocks it is somewhat more abundant in basic types; very rarely is it more than an accessory constituent. Finally it is found in dikes, veins, and pegmatites, sometimes in large crystals.

**DIAG.** Apatite in its common crystal form is readily distinguished from most other minerals by that means;

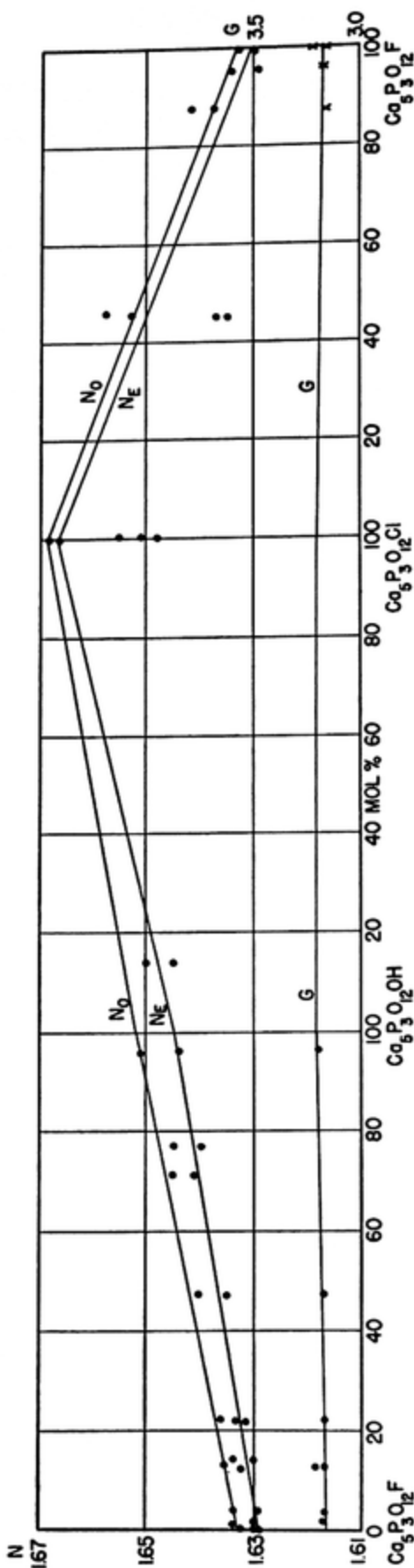


Fig. 112. Properties of the fluor-, hydroxyl-, and chlor-apatite double series.

also by its moderate relief, very weak birefringence, and lack of distinct cleavage (except in dehrnite and lewistonite). Apatite differs from quartz in having higher relief, weaker birefringence (except podolite and types with  $\text{CO}_3$ ), and negative sign. Anhedral apatite is more easily confused with other minerals; it is distinguished from eudialite

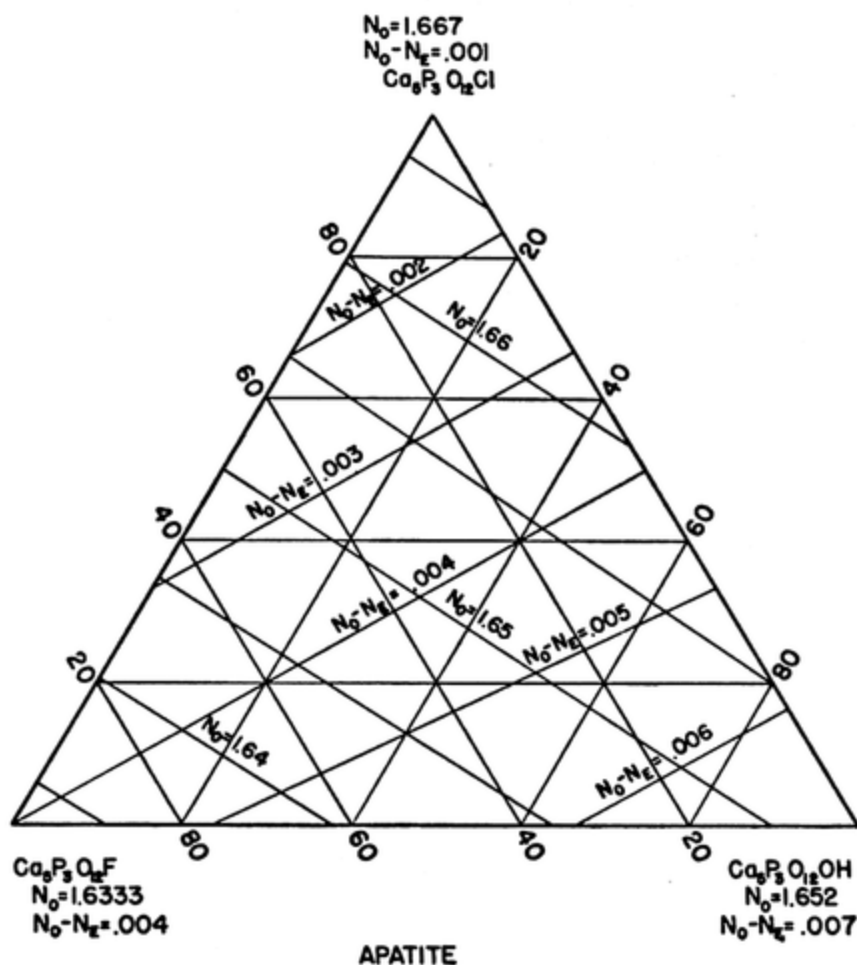


FIG. 113. Properties of the fluor-, hydroxyl-, and chlor-apatite system.

by somewhat higher refraction, absence of distinct cleavage, and chemical reactions; melilite is optically of variable sign, has distinct cleavage and usually shows abnormal interference colors; gehlenite has somewhat higher relief than apatite; vesuvianite has still higher relief.

**Pyromorphite** ( $\text{Pb}_5\text{ClP}_3\text{O}_{12}$ ) is hexagonal dipyramidal with  $c/a = 0.736$ .  $a$  9.95,  $c$  7.31 Å.<sup>76</sup> Crystals prismatic, horizontally striated, with very poor prismatic and pyramidal cleavages.  $H. = 4$ .  $G. = 7.14$ .  $F. = 1156^\circ \text{C}$ . Soluble in  $\text{HNO}_3$ . Uniaxial negative with  $N_O = 2.0443$  Li, 2.0596 Na, 2.0899 (491.6),  $N_E = 2.0340$  Li, 2.0488 Na, 2.0787 (491.6),  $N_O - N_E = 0.0108$  Na. Again:<sup>90</sup>  $N_O = 2.0504$  C, 2.0614 D, 2.0964 F,  $N_E = 2.042$  C, 2.0494 D, 2.0832 F,  $N_O - N_E = 0.0120$  D. Also biaxial when As is present; the optic angle is small, decreasing with decrease in tenor

<sup>90</sup> H. L. Bowman: *Mineral. Mag.*, XIII, 324 (1903).

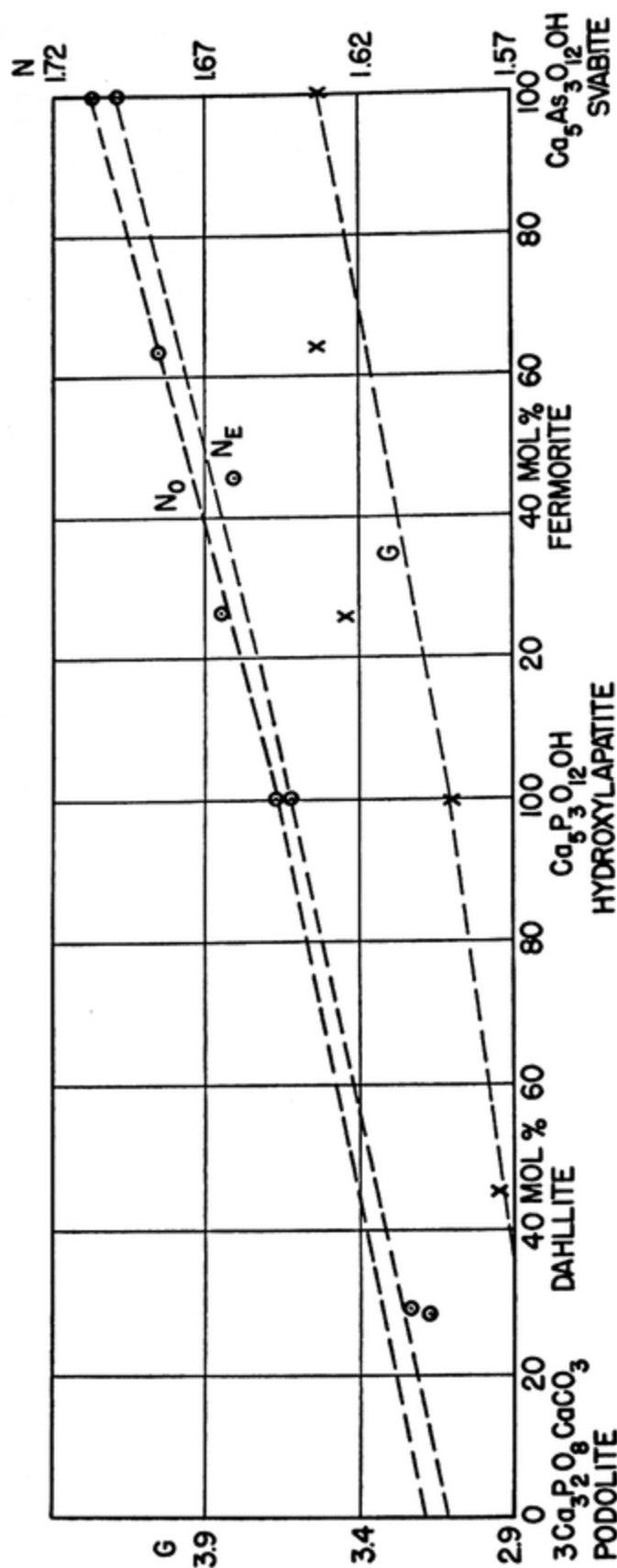


FIG. 114. Properties of the podolite, hydroxylapatite, and svabite double series.

of As. Color green, yellow, brown, gray, white; colorless or weakly pleochroic in section with  $O =$  green,  $E =$  yellow to greenish yellow, and  $O > E$ . Alters rarely to cerussite or even galena. Found in the oxide zone of lead deposits. Pyromorphite is exceptional in combining moderate birefringence with very high relief; it differs from apatite in its mode of occurrence and much higher relief, and from vanadinite in its much weaker birefringence; mimetite is usually distinctly biaxial.

**Vanadinite** ( $Pb_5ClV_3O_{12}$ ) is hexagonal dipyramidal with  $c/a = 0.712$ .  $a$  10.31,  $c$  7.34 Å.<sup>76</sup> Crystals prismatic to fibrous.  $H. = 3$ .  $G. = 7.0 \pm$ .  $F. = 990^\circ C$ . Decomposed by HCl. Uniaxial negative with  $^{91} N_O = 2.3761$  Li, 2.4163 Na, 2.5053 (491.6),  $N_E = 2.3186$  Li, 2.3503 Na, 2.4229 (491.6),  $N_O - N_E = 0.066$  Na. Color red, yellow, brown; colorless in section or pleochroic with  $O =$  brownish red to

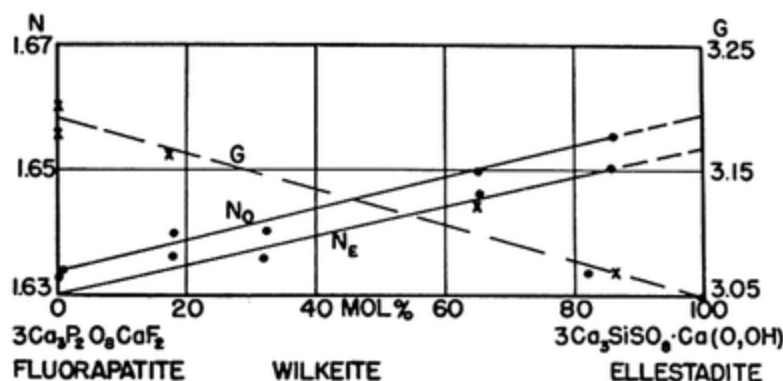


FIG. 115. Properties of the fluorapatite-ellestadite series.

orange,  $E =$  lemon yellow with reddish spots, and  $O > E$ . Found in the oxide zone of lead deposits. Not common. Vanadinite has stronger birefringence than any other member of the apatite group. Lacroix notes that by treating the mineral on an object glass with dilute nitric acid and evaporating to dryness the residue is dark red if the mineral is vanadinite, lighter red if endlichite, and colorless if any other member of the apatite group.

**Endlichite**<sup>92</sup> is a variety of vanadinite containing arsenic, with  $V:As = 1:1$  nearly; it is uniaxial (or slightly biaxial) with  $N_O = 2.358$  D,  $N_E = 2.311$ ,  $N_O - N_E = 0.047$ . Another crystal gave  $N_O = 2.25$ ,  $N_E = 2.20$ ,  $N_O - N_E = 0.05$ . Color yellow.

**Mimetite** ( $Pb_5ClAs_3O_{12}$ ) is hexagonal dipyramidal with  $c/a = 0.725$ .  $a$  10.24,  $c$  7.43 Å.<sup>76</sup> Poor prismatic cleavage.  $H. = 3.5$ .  $G. = 7.15$ .  $F. = 1140^\circ C$ . Soluble in  $HNO_3$ . Uniaxial negative with  $N_O = 2.135$ ,  $N_E = 2.120$ ,  $N_O - N_E = 0.015$  (Larsen<sup>77</sup>).  $N_O = 2.144$ – $2.149$ ,  $N_E = 2.129$ – $2.135$ ,  $N_O - N_E = 0.014$ – $0.018$  (Bowman<sup>90</sup>).  $N_O = 2.1242$  Li, 2.1434 Na, 2.1839 (491.6),  $N_E = 2.1073$  Li, 2.1261 Na, 2.1657 (491.6),  $N_O - N_E = 0.0173$  Na (Lietz<sup>91</sup>). Also biaxial,  $2E$  attaining  $64^\circ$ ; basal sections show six sectors, each having the optic plane parallel to the hexagonal face and  $X$  normal to the base. Color yellow, brown, or white; colorless in section or weakly pleochroic in yellow tints with  $O > E$ . Found in the oxide zone of lead deposits, as at Långban, Sweden.

<sup>91</sup> J. Lietz: *Zeit. Krist.*, LXXVII, 437 (1931).

<sup>92</sup> Endlichite strongly suggests a continuous series from vanadinite to mimetite.



*Hedyphane* is a variety of mimetite containing 5 to 15% of CaO. Uniaxial negative<sup>93</sup> with  $N_O = 2.026$ ,  $N_E = 2.010$ ,  $N_O - N_E = 0.016$ . Color bluish. Found at Franklin, New Jersey.

**Alluaudite**<sup>94</sup>  $[Na_4(Mn''', Fe''')_{15}(F, OH)_4(PO_4)_{10}]$  is orthorhombic and related to triphylite. It has three rectangular cleavages.  $G. = 3.576$ .  $Z$  normal to best cleavage.  $(+2V) = \text{moderate}$ ,  $N_X = 1.760$ ,  $N_Y = 1.765$  (calc.),  $N_Z = 1.775$ ,  $N_Z - N_X = 0.015$ . Again:<sup>95</sup>  $N_X = 1.752$ ,  $N_Y = ?$ ,  $N_Z = 1.764$ ,  $N_Z - N_X = 0.012$ . Color yellow, brownish, or green and non- or weakly pleochroic. It is produced by the oxidation of varulite or natrophilite at Varuträsk, Sweden.

**Carminite**<sup>17</sup>  $[PbFe_2(OH)_2As_2O_8]$  is orthorhombic dipyramidal with  $a:b:c = 0.737:1:0.466$ . Crystals {010} tablets, with perfect prismatic cleavage.  $H. = 2.5-3$ .  $G. = 4.1$ .  $F. = \text{easy}$ . Soluble in  $HNO_3$ .  $(+2V) = \text{moderate}$ ,  $r < v$  strong.

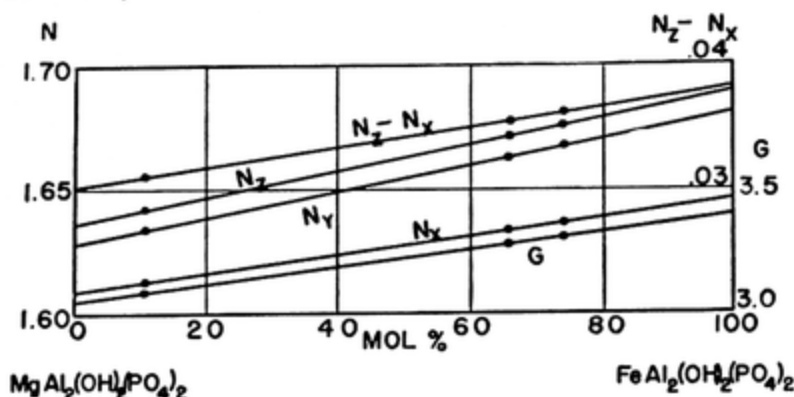


FIG. 116. Properties of lazulite. See W. T. Pecora and J. J. Fahey: *Bull. Geol. Soc. Am.*, LVIII, 1216 (1947).

$N_X = 2.070$ ,  $N_Y = 2.070$ ,  $N_Z = 2.080$ ,  $N_Z - N_X = 0.010$ . Elongation negative. Color carmine red to reddish brown; pleochroic with  $X = \text{pale yellowish red}$ ,  $Y = Z = \text{dark carmine red}$ . Found in ore deposits, as at Calstock, Cornwall.

**Lazulite**  $[(Mg, Fe)(AlOH)_2(PO_4)_2]$  is monoclinic prismatic with  $a:b:c = 0.975:1:1.694$ ,  $\beta = 91^\circ 58'$ . Lazulite with  $Fe > Mg$  has been called *scorzalite*.<sup>96</sup> Crystals acute pyramids; lamellar twinning<sup>97</sup> on 110, 101; indistinct 110 cleavage.  $H. = 5-6$ .  $G. = 3.1$ .  $F. = 7$ . Insoluble in  $HCl$ . The optic plane is 010;  $X \wedge c = +9^\circ$  to  $+10^\circ$ .  $(-2V) = 69^\circ \pm$ ,  $r < v$  weak. With  $Mg:Fe = 9:1$ ,  $G. = 3.08$ ,  $N_X = 1.612$ ,  $N_Y = 1.634$ ,  $N_Z = 1.643$ ,  $N_Z - N_X = 0.031$  (Palache<sup>98</sup>). With  $Mg:Fe = 1:2$ ,  $G. = 3.33$ ,  $N_X = 1.637$ ,  $N_Y = 1.663$ ,  $N_Z = 1.673$ ,  $N_Z - N_X = 0.036$  (Pecora<sup>96</sup>). See Fig. 116. Color azure to Prussian blue, with  $X = \text{colorless}$ ,  $Y = Z = \text{azure blue}$ . Inclusions with movable bubbles may be abundant. Found in veins in quartzite, etc. Distinguished from lazurite, blue tourmaline, and blue corundum by its pleochroism and biaxial character; from blue cordierite, sapphirine, and dumortierite by its strong birefringence, and from blue kyanite and blue amphibole by the absence of cleavage.

<sup>93</sup> C. Palache: *U. S. Geol. Surv. Prof. Paper* 180 (1935).

<sup>94</sup> P. Quensel: *Geol. För. Förh.*, LIX, 77 (1937); a new formula  $[(Na, Mn'', Fe''')PO_4]$  proposed by B. Mason: *Geol. För. Förh.*, LXIII, 117 (1941).

<sup>95</sup> B. Mason: *Geol. För. Förh.*, LXII, 369 (1941).

<sup>96</sup> W. T. Pecora and J. J. Fahey: *Bull. Geol. Soc. Am.*, LVIII, 1217 (1947).

<sup>97</sup> E. Baier: *Min. Abst.*, VIII, 382 (1943).

<sup>98</sup> C. Palache and F. A. Gonyer: *Am. Mineral.*, XV, 338 (1930).

## (b) WITH ADDITIONAL ANIONS—HYDROUS

## PHARMACOSIDERITE

ISOMETRIC <sup>99</sup>

COMP. May contain P and K; perhaps also  $\text{FeAsO}_4 \cdot \text{H}_2\text{O}$ . Formula  $\text{Fe}_5(\text{OH})_6\text{As}_3\text{O}_{12} \cdot 6\text{H}_2\text{O} (?)$  or  $\text{KFe}_4(\text{OH})_4\text{As}_3\text{O}_{12} \cdot 6$  or  $7\text{H}_2\text{O}?$ .

STRUC.<sup>100</sup> Space group  $P\bar{4}3m$ ;  $a$  7.94 Å. U.C. 1.

PHYS. CHAR. Crystals cubes with tetrahedrons; poor cubic cleavage.  $H. = 2.5$ .  $G. = 3.0$ .  $F. = 1$ . Soluble in HCl.

OPT. PROP. Nearly isotropic with  $N = 1.676$  (Gaubert <sup>101</sup>);  $N = 1.693$  (Larsen <sup>27</sup>); but anisotropic at ordinary temperature with  $N_z - N_x = 0.005$ , doubtless due to inversion to a monoclinic phase. Also <sup>102</sup>  $N = 1.687$  in a yellow crystal, and  $N = 1.704$  in a green crystal (containing K). Sections parallel to cubic faces are divided into four segments by diagonals, or into one central square area and four bordering segments, the latter sometimes having lamellar twinning parallel to the edges.  $(- )2V =$  small to moderate,  $r > v$  very strong, with or without strong dispersion of the bisectrices resulting in abnormal interference colors. Some fragments are optically positive. In bordering segments extinction is parallel to the edges (Lacroix) or at large angles (Larsen). On heating, the border zones change, the indices gradually become equal (isotropic) and then change places. The anisotropic crystals are monoclinic with the optic plane parallel to 010 (Lacroix).

Color green, yellow, brown. Crystals quickly absorb  $\text{NH}_4\text{OH}$ , becoming red; then in dilute HCl they revert to their original color.

OCCUR. Pharmacosiderite is found in the oxide zone of copper and tin ore deposits where it forms from the alteration of arsenopyrite, enargite, etc., as in Cornwall, Bohemia, and Utah.

DIAG. The cubic form and optic properties are characteristic.

**Cahnite** <sup>103</sup>  $(\text{CaB}_2\text{O}_4 \cdot \text{Ca}_3\text{As}_2\text{O}_8 \cdot 4\text{H}_2\text{O})$  is tetragonal disphenoidal with  $c/a = 0.615$ . Shows interpenetration twinning.  $H. = 3$ .  $G. = 3.156$ .  $F. = 7$ . Soluble in HCl. Uniaxial positive with  $N_O = 1.662$ ,  $N_E = 1.663$ ,  $N_E - N_O = 0.001$ . Strong dispersion and abnormal interference colors. Found at Franklin, New Jersey.

**Sincosite**  $[\text{Ca}(\text{VO}_2)_2\text{P}_2\text{O}_8 \cdot 5\text{H}_2\text{O}]$  is tetragonal in rectangular basal plates with distinct 001 cleavage.  $G. = 2.84$ . Soluble in dilute acid. Uniaxial negative with  $N_O = 1.680$ ,  $N_E = 1.655$ ,  $N_O - N_E = 0.025$ . Also biaxial (altered?) with  $(- )2E = 0-80^\circ$ ,  $r > v$  strong,  $N_X = 1.675$ ,  $N_Y = 1.690$ ,  $N_Z = 1.693$ ,  $N_Z - N_X = 0.018$ . Color emerald green to brass yellow with  $X =$  colorless to pale yellow,  $Y = ?$ ,  $Z =$  gray-green. Found in shale at Sincos, Peru.

## URANITE GROUP

The minerals of the uranite group are tetragonal (?orthorhombic and monoclinic) phosphates and arsenates of uranium with copper, calcium, barium, or magnesium. The following types are known:

<sup>99</sup> R. Hocart: *Bull. Soc. Fr. Min.*, LVII, 5 (1934). See also J. Zemann: *Tsch. Min. Pet. Mit.*, 3 Ser. I, 1 (1948).

<sup>100</sup> G. Hägele and F. Machatschki: *Min. Abst.*, VII, 147 (1938).

<sup>101</sup> P. Gaubert: *Bull. Soc. Fr. Min.*, XXX, 104 (1907).

<sup>102</sup> F. Heide: *Zeit. Krist.*, LXVII, 60 (1928).

<sup>103</sup> C. Palache and L. H. Bauer: *Am. Mineral.*, XII, 149 (1927).

Saléeite  $Mg(UO_2)_2P_2O_8 \cdot 10H_2O$

Autunite  $Ca(UO_2)_2P_2O_8 \cdot 10H_2O$

Uranospinite  $Ca(UO_2)_2As_2O_8 \cdot 12(?)H_2O$

Torbernite  $Cu(UO_2)_2P_2O_8 \cdot 12H_2O$

Zeunerite  $Cu(UO_2)_2As_2O_8 \cdot 12(?)H_2O$

Uranocircite  $Ba(UO_2)_2As_2O_8 \cdot 12(?)H_2O$

Troegerite  $(UO_2)_3As_2O_8 \cdot 12H_2O$

Meta-saléeite  $Mg(UO_2)_2P_2O_8 \cdot 8H_2O$

{ Meta-autunite-I  $Ca(UO_2)_2P_2O_8 \cdot 6H_2O$

{ Meta-autunite-II  $Ca(UO_2)_2P_2O_8 \cdot 2H_2O$

Bassetite  $Fe(UO_2)_2P_2O_8 \cdot 8(?)H_2O$

Metatorbernite  $Cu(UO_2)_2P_2O_8 \cdot 8H_2O$

Metazeunerite  $Cu(UO_2)_2As_2O_8 \cdot 8(?)H_2O$

Phosphuranylite  $[(UO_2)_3P_2O_8 \cdot 6(?)H_2O]$ , tyuyamunite  $[Ca(UO_2)_2V_2O_8 \cdot 4 \pm H_2O?]$ , sincosite  $[Ca(VO_2)_2P_2O_8 \cdot 5H_2O?]$ , and carnotite  $[K_2(UO_2)_2V_2O_8 \cdot 4 \pm H_2O?]$  seem to be related to this group.

**Saléeite**  $[Mg(UO_2)_2P_2O_8 \cdot 10H_2O]$  is ditetragonal dipyramidal<sup>104</sup> with  $c/a = 2.839$ . Perfect 001 cleavage.  $H. = 2.5$ .  $G. = 3.27$ .  $(-)2V = 0^\circ$ ,  $N_O = 1.574$ ,  $N_E = 1.559$ ,  $N_O - N_E = 0.015$ . Color yellow. Found at Schneeberg, Saxony.

**Meta-saléeite**  $[Mg(UO_2)_2P_2O_8 \cdot 8H_2O]$  is monoclinic.<sup>104</sup> Crystals {010} tablets with 010, 100, and 001 cleavages.  $H. = 2$ .  $G. = 3.3$ . The optic plane is 001.  $(-)2V = 61^\circ$ ,  $r > v$ . Color yellow. Found in the Belgian Congo.

## AUTUNITE

$Ca(UO_2)_2P_2O_8 \cdot 10H_2O$

DITETRAGONAL DIPYRAMIDAL  $c/a = 2.952$

**COMP.** The tenor of water varies easily, but 10 (or  $10\frac{1}{2}$ )  $H_2O$  has relative stability. Ca can be entirely replaced<sup>105</sup> by Na, K, Ba, Mn, Cu, Ni, Pb, or Mg.

**STRUC.** Space group<sup>106</sup>  $I4/mmm$ ;  $a$  6.99,  $c$  20.63 Å. U.C. 2.

**PHYS. CHAR.** Crystals thin basal tablets or micaceous masses. Perfect 001 and good 100, 010, and 110 cleavages.  $H. = 2-2.5$ .  $G. = 3.14$ .  $F. = 3$ . Soluble in  $HNO_3$ .

**OPT. PROP.** With maximum tenor of water the crystals are biaxial, but they become uniaxial on losing water. They may even become biaxial with the optic

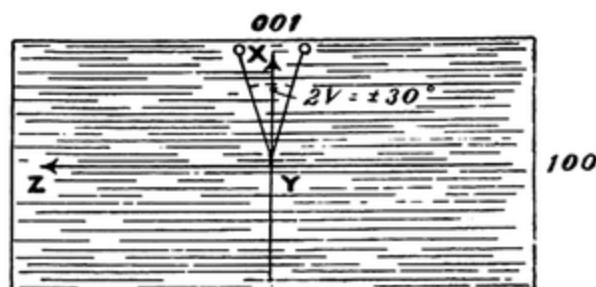


FIG. 117. The optic orientation of autunite.

plane normal to its first position. The optic plane is 010;  $X = c$ . See Fig. 117.  $(-)2V = 33^\circ$ , but variable,  $r > v$  strong.  $N_X = 1.553$ ,  $N_Y = 1.575$ ,  $N_Z = 1.577$ ,  $N_Z - N_X = 0.024$ . Again:<sup>107</sup>  $N_Y = 1.596$  and  $2E = 45^\circ$  on autunite from Bo-

<sup>104</sup> L. J. Spencer: *Min. Mag.*, XXV, 643 (1940); M. E. Mrose: *Am. Mineral.*, XXXV, 525 (1950).

<sup>105</sup> J. G. Fairchild: *Am. Mineral.*, XIV, 265 (1929).

<sup>106</sup> J. Beintema: *Rec. Trav. Chim. Pays-Bas*, LVII, 155 (1938).

<sup>107</sup> B. Stočes: *Roz. České Akad.*, XXVII, No. 27 (1918); *Min. Abst.*, I, 291 (1922).

hemia. *Uranospathite*<sup>108</sup> is perhaps an autunite with more water ( $12\text{H}_2\text{O}$ ?). It has  $X = c$ ,  $Y = b$ ,  $(- )2V = 69^\circ$ ,  $N_X = 1.488$  (calc.),  $N_Y = 1.510$ ,  $N_Z = 1.521$ ,  $N_Z - N_X = 0.033$  (calc.). Color yellow with  $X =$  pale yellow,  $Y$  and  $Z =$  deep yellow. Autunite is lemon to sulfur yellow and weakly pleochroic with  $X =$  colorless,  $Y$  and  $Z =$  golden yellow.

**OCCUR.** Found with uraninite and also with silver, tin, and iron ores, as in the Black Hills, South Dakota.

**DIAG.** Autunite is characterized by its golden-yellow color, brittle laminae, and acute negative bisectrix normal to micaceous cleavage.

**Meta-autunite-I**<sup>109</sup>  $[\text{Ca}(\text{UO}_2)_2\text{P}_2\text{O}_8 \cdot 6\text{H}_2\text{O}]$  has a water content which varies from 2.5 to 6.5  $\text{H}_2\text{O}$ . It is ditetragonal dipyramidal with  $c/a = 1.206$ ; space group  $I4/mmm$ .  $a$  6.98,  $c$  8.42 Å. U.C. 1.  $G. > 3.33$  (about 3.57?). Refrindex not measured; birefringence weak. Biaxial, but it becomes uniaxial at about  $60^\circ\text{C}$ . Color yellow. Easily produced by partial dehydration of autunite (a reversible change). Further dehydration produces meta-autunite-II, but this change is not reversible.

**Meta-autunite-II**<sup>109</sup>  $[\text{Ca}(\text{UO}_2)_2\text{P}_2\text{O}_8 \cdot 2\text{H}_2\text{O}]$  has a water content varying from 0 to 6  $\text{H}_2\text{O}$ . It is probably orthorhombic dipyramidal with  $a:b:c = 0.926:1:1.241$ ; space group probably  $Pmmm$ .  $a$  6.45,  $b$  6.97,  $c$  8.65 Å. Refrindex not measured; birefringence strong.

**Uranospinite**  $[\text{Ca}(\text{UO}_2)_2\text{As}_2\text{O}_8 \cdot 12(?)\text{H}_2\text{O}]$  is pseudotetragonal and orthorhombic dipyramidal with  $a:b:c = 1 \pm 1:2.914$ . Crystals square basal tablets with perfect 001 cleavage.  $H. = 2-3$ .  $G. = 3.45$ . Fusible. Soluble in acid. Uniaxial negative with  $N_O = 1.586$ ,  $N_E = 1.56$ ,  $N_O - N_E = 0.026 \pm$ . Color yellow with  $O =$  pale yellowish,  $E =$  nearly colorless. A single crystal may have this uniaxial condition as a border and a main portion which is biaxial with  $X$  normal to the plate,  $Z$  parallel to the elongation, and  $(- )2V = 46^\circ$ ,  $r > v$  rather strong;  $N_X = 1.560$ ,  $N_Y = 1.582$ ,  $N_Z = 1.587$ ,  $N_Z - N_X = 0.027$ . Color yellow with  $X =$  nearly colorless,  $Y$  and  $Z =$  pale canary yellow. Found with uraninite in Saxony.

**Bassetite**<sup>108</sup>  $[\text{Fe}(\text{UO}_2)_2\text{P}_2\text{O}_8 \cdot 8(?)\text{H}_2\text{O}]$  is monoclinic with  $a:b:c = 0.347:1:0.346$ ,  $\beta = 90^\circ 43'$ . Crystals {010} tablets with perfect 010 and good 100 and 001 cleavages. Complex lamellar twinning.  $G. = 3.10$ . The optic plane is normal to 010;  $Z \wedge c = +4^\circ$ .  $(- )2E = 110^\circ$ ,  $N_X = 1.558$  (calc.),  $N_Y = 1.574$ ,  $N_Z = 1.580$ ,  $N_Z - N_X = 0.022$  (calc.). Color yellow with  $X =$  pale yellow,  $Y$  and  $Z =$  deep yellow. In a desiccator the extinction angle increases to about  $20^\circ$ . Found in Cornwall.

**Torbernite**  $[\text{Cu}(\text{UO}_2)_2\text{P}_2\text{O}_8 \cdot 12\text{H}_2\text{O}]$  is ditetragonal dipyramidal<sup>110</sup> with  $c/a = 2.90$ . Space group<sup>111</sup>  $I4/mmm$ .  $a$  7.05,  $c$  20.5 Å. U.C. 2. Crystals square basal tablets, pyramidal, or micaceous masses, with perfect 001 and distinct 100 cleavages.  $H. = 2-2.5$ .  $G. = 3.22$ .  $F. = 2.5$ . Soluble in  $\text{HNO}_3$ . Nearly uniaxial and negative with  $N_O = 1.592$ ,  $N_E = 1.582$ ,  $N_O - N_E = 0.010$ . With 2.83%  $\text{As}_2\text{O}_5$ , it has  $G.$ <sup>112</sup>  $= 3.7$ ,  $N_O = 1.6204$ . Color light to dark green with  $O =$  greenish yellow,  $E =$  pale green or pale blue. The mineral shows five well-defined absorption bands

<sup>108</sup> A. F. Hallimond: *Mineral. Mag.*, XVII, 221 (1915). H. Meixner: *Chem. Erde*, XII, 433 (1940).

<sup>109</sup> F. Rinne: *Cent. Min.*, 1901, 709; J. Beintema: *Rec. Trav. Chim. Pays-Bas*, LVII, 155 (1938).

<sup>110</sup> Also considered orthorhombic with  $a:b:c = 1:1:2.974$ .

<sup>111</sup> S. Goldsztaub: *Bull. Soc. Fr. Min.*, LV, 6 (1932).

<sup>112</sup> A. Pelloux: *Min. Abst.*, VI, 518 (1937).

between 440 and 510  $m\mu$ . Found in veins in schists and granite, as at Tincroft, Cornwall.

**Metatorbernite**  $[Cu(UO_2)_2P_2O_8 \cdot 8H_2O]$  is (nearly) tetragonal with  $c/a = 2.28$ . Crystals square basal tablets with perfect 001 and good 100 cleavages.  $H. = 2.5$ .  $G. = 3.67$ .  $F. = 2.5$ . Soluble in  $HNO_3$ . Uniaxial and positive (in white light) with abnormal dispersion of the indices, thus: <sup>113</sup>

$\lambda =$	640 $m\mu$	589 $m\mu$	550 $m\mu$	575 $m\mu$	480 $m\mu$	440 $m\mu$
$N_O =$	1.619	1.624	1.629	1.6335	1.640	1.6495
$N_E =$	1.622(5)	1.626	1.630	1.6335	1.638	1.6465
$N_E - N_O =$	0.003(5)	0.002	0.001	0.0000	(-)0.002	(-)0.003

The mineral is therefore isotropic in green light (515  $m\mu$ ), positive in red and yellow light, and negative in blue light. The interference colors are quite abnormal, being confined to red and blue. Stočes <sup>107</sup> reported  $2E =$  very small to  $30^\circ$  and  $N_Y = 1.610$  to  $1.628$  in different samples. Metatorbernite is easily formed by partial dehydration of torbernite at  $60-65^\circ C$ . It is found in Cornwall and Spain. Hallimond <sup>114</sup> argues that the dehydration occurs only through vertical faces and not through the base; he thinks the water exists between basal layers of atoms, and the change in axial ratio is in harmony with this view.

**Zeunerite**  $[Cu(UO_2)_2As_2O_8 \cdot 12(?)H_2O]$  is (nearly) tetragonal with  $c/a = 2.91$ . Crystals basal tablets with perfect 001 and good 100 cleavages.  $H. = 2-2.5$ .  $G. = 3.2$ .  $F. = 3$ . Soluble in  $HNO_3$ . Nearly uniaxial and negative with  $N_O = 1.643$ ,  $N_E = 1.623$ ,  $N_O - N_E = 0.020$ . Color apple to emerald green; pale green in section with  $E < O$ . Found on quartz in copper ores, as at Wheal Gorland, Cornwall.

**Metazeunerite**  $[Cu(UO_2)_2As_2O_8 \cdot 8(?)H_2O]$  is similar. Ježek <sup>115</sup> found that "zeunerite" (probably metazeunerite) had  $G. = 3.28$  and was uniaxial negative with  $N_O = 1.585$ ,  $N_E = 1.576$ ,  $N_O - N_E = 0.009$ . Color green with  $E =$  bluish,  $O =$  emerald green.

**Uranocircite**  $[Ba(UO_2)_2As_2O_8 \cdot 12(?)H_2O]$  is (nearly) tetragonal in basal tablets with perfect 001 and good 100 and 010 cleavages.  $H. = 2$ .  $G. = 3.5$ . Soluble in  $HCl$ . Nearly uniaxial with  $(-)2V = 10^\circ$ ,  $N_O = 1.623$ ,  $N_E = 1.610$ ,  $N_O - N_E = 0.013$ . Color yellow-green, with  $O =$  pale canary yellow,  $E =$  colorless. Two sets of lamellar twinning at right angles visible in basal plates. Found in quartz veins at Falkenstein, Germany.

**Troegerite**  $[(UO_2)_3As_2O_8 \cdot 12H_2O]$  is (nearly) tetragonal with  $c/a = 2.16$  (perhaps monoclinic). Crystals are basal tablets with perfect 001 and good 010 cleavages.  $H. =$  soft.  $G. = 3.3$ .  $F. = 2.5$ . Soluble in acid. Uniaxial negative with  $N_O = 1.627$ ,  $N_E = 1.582$ ,  $N_O - N_E = 0.045$ . Also slightly biaxial with  $N_X = 1.585$ ,  $N_Y$  and  $N_Z = 1.630$ ,  $N_Z - N_X = 0.045$ . If monoclinic, crystals are 010 plates and  $Z \wedge c = 12^\circ$ . Color lemon yellow. Found with walpurgite at Neustädtel, Germany.

**Phosphuranylite**  $[(UO_2)_3P_2O_8 \cdot 6(?)H_2O]$  is nearly tetragonal and probably monoclinic. Crystals {010} tablets. Soluble in  $HCl$ .  $X = b$ .  $(-)2V =$  nearly  $0^\circ$ , with very strong dispersion.  $N_X = 1.691$ ,  $N_Y = 1.720$ ,  $N_Z = 1.720$ ,  $N_Z - N_X = 0.029$ . Color deep lemon yellow with  $X =$  nearly colorless,  $Y$  and  $Z =$  canary yellow. Found in mines in North Carolina.

<sup>113</sup> From graph of N. L. Bowen: *Am. Jour. Sci.*, CXCVIII, 195 (1919).

<sup>114</sup> A. F. Hallimond: *Mineral. Mag.*, XVII, 326 (1916), and XIX, 43 (1920).

<sup>115</sup> B. Ježek: *Min. Abst.*, II, 353 (1924).



**Tyuyamunite**  $[\text{Ca}(\text{UO}_2)_2\text{V}_2\text{O}_8 \cdot 4\pm\text{H}_2\text{O}]$  is orthorhombic<sup>116</sup> with  $a:b:c = 0.557:1:0.428$ . Crystals {010} plates with perfect 010 and poor 001 and 100 cleavages. H. = soft. G. = 3.7–4.3, varying with tenor of water.  $X = b$ ,  $Y = c$ .  $(- )2V = 36^\circ\text{--}55^\circ$ ,  $r < v$  rather strong.  $N_X = 1.670$ ,  $N_Y = 1.870$ ,  $N_Z = 1.895$ ,  $N_Z - N_X = 0.235$ . Other measures gave:

	Merwin <sup>117</sup>	Rode <sup>118</sup>	Ross <sup>119</sup>
$(- )2V =$		48°	48°
$N_X = 1.75\text{--}1.80$ calc.	1.78 calc.		1.72
$N_Y = 1.927\text{--}1.932$	1.895		1.868
$N_Z = 1.965\text{--}1.968$	1.92		1.953
$N_Z - N_X = 0.044$	0.14	0.154	0.233

Color yellow with  $X =$  nearly colorless,  $Y =$  canary yellow,  $Z =$  darker canary yellow. In potassium mercuric iodide the Ca is slowly replaced by  $\text{K}_2$  with decrease in  $\text{H}_2\text{O}$ . Found in Colorado and U. S. S. R.

**Ceruleolactite**  $[\text{Al}_6(\text{OH})_6(\text{PO}_4)_4 \cdot 7\text{H}_2\text{O}]$  is fibrous in crusts. H. = 5. G. = 2.55–2.7. F. = 7. Soluble in HCl. Uniaxial positive with  $N_O = 1.580$ ,  $N_E = 1.588$ ,  $N_E - N_O = 0.008$ . Color white to light blue. Found in the oxide zone of ore deposits.

**Minyulite**<sup>120</sup>  $[\text{KAl}_2(\text{OH},\text{F})\text{P}_2\text{O}_8 \cdot 4\text{H}_2\text{O}]$  is orthorhombic pyramidal with  $a:b:c = 0.956:1:0.563$ . Space group  $Pmm$ ;  $a$  9.35,  $b$  9.74,  $c$  5.52 Å. U.C. 2. Perfect basal cleavage. H. = 3.5. G. = 2.45. Soluble in acid. Fibrous with a silky luster.  $X = c$ ,  $Y = a$ .  $(+ )2V =$  large,  $N_X = 1.531$ ,  $N_Y = 1.534$ ,  $N_Z = 1.538$ ,  $N_Z - N_X = 0.007$ . With more F:  $N_X = 1.525$ ,  $N_Y = ?$ ,  $N_Z = 1.530$ ,  $N_Z - N_X = 0.005$ . Colorless to white. Found in veins in phosphatic ironstone at Dandaragan, Western Australia.

**Landesite**<sup>45</sup>  $[\text{Mn}_{10}\text{Fe}_3(\text{OH})_6(\text{PO}_4)_8 \cdot 11\text{H}_2\text{O}]$  is probably orthorhombic; if the good cleavage is 010 and another cleavage is 001, the optic plane is 100 and  $X = c$ .  $(- )2V =$  large.  $N_X = 1.720$ ,  $N_Y = 1.728$ ,  $N_Z = 1.735$ ,  $N_Z - N_X = 0.015$ . Color brown with  $X =$  dark brown,  $Y =$  light brown,  $Z =$  yellow. Found as an alteration product of reddingite at Poland, Maine.

**Sengierite**<sup>121</sup>  $[\text{Cu}_2(\text{UO}_2)_2\text{OHV}_2\text{O}_8 \cdot 10\text{H}_2\text{O}]$  is orthorhombic with  $a:b:c = 0.762:1:0.739$ . Crystals rhombic plates with perfect basal cleavage. H. = 2.5. G. = 4 ca.  $X = c$ ,  $Y = b$ ,  $(- )2V = 37^\circ\text{--}39^\circ$ ,  $r < v$  strong;  $N_X = 1.77$ ,  $N_Y = 1.94$ ,  $N_Z = 1.97$ ,  $N_Z - N_X = 0.20$ . Color green with  $X =$  bluish green to colorless,  $Y =$  olive green,  $Z =$  yellowish green. Found in the Belgian Congo.

**Sterrettite**<sup>122</sup>  $[\text{Al}_6(\text{OH})_6\text{P}_4\text{O}_{16} \cdot 5\text{H}_2\text{O}]$  is orthorhombic disphenoidal with  $a:b:c = 0.866:1:0.532$ . Space group  $P2_12_12_1$ ;  $a$  8.90,  $b$  10.20,  $c$  5.43 Å. U.C. 1. Crystals

<sup>116</sup> P. N. Chirvinsky: *Mineral. Mag.*, XX, 287 (1924);  $b$  and  $c$  interchanged to make  $b > a > c$ .

<sup>117</sup> W. F. Hillebrand: *Am. Jour. Sci.*, CCVIII, 208 (1924).

<sup>118</sup> E. Y. Rode: *Min. Abst.*, III, 447 (1928). With 17.53  $\text{H}_2\text{O}$ .

<sup>119</sup> C. S. Ross: *U. S. Geol. Surv. Bull.* 750-D, 73 (1924); Ross states that  $N_Z$  and  $N_Y$  are of doubtful accuracy because the mineral loses water in melts of S and Se.

<sup>120</sup> E. S. Simpson and C. R. LeMesurier: *Jour. Roy. Soc. W. Australia*, XIX, 13 (1932); L. J. Spencer *et al.*: *Min. Mag.*, XXVI, 309 (1943).

<sup>121</sup> J. F. Vaes and P. F. Kerr: *Am. Mineral.*, XXXIV, 109 (1949).

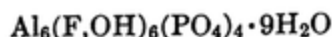
<sup>122</sup> E. S. Larsen, 3rd, and A. Montgomery: *Am. Mineral.*, XXV, 513 (1940).



domatic with fair 110 cleavage.  $H. = 5$ .  $G. = 2.36$ . The optic plane is 010;  $X = a$ .  $(- )2V = 60^\circ \pm 10^\circ$ ,  $r > v$ , weak.  $N_X = 1.572$ ,  $N_Y = 1.590$ ,  $N_Z = 1.601$ ,  $N_Z - N_X = 0.029$ . Colorless. Found in pseudowavellite in variscite deposits at Fairfield, Utah.

# WAVELLITE

ORTHORHOMBIC



$$a:b:c = 0.564:1:0.408$$

COMP. Wavellite may contain iron, both ferrous and ferric.

STRUC. <sup>123</sup>  $a$  9.7,  $b$  17.4,  $c$  7.07 Å. U.C. 2.

PHYS. CHAR. Crystals very rare; fibrous, radiated. Good 110, 011, and 010 cleavages.  $H. = 3.5-4$ .  $G. = 2.36$ .  $F. = 7$ , but swells and gives green flame color. Soluble in  $H_2SO_4$  and in NaOH.

OPT. PROP. The optic plane is 100;  $Z = c$ , parallel to elongation.  $(+ )2V = 72^\circ$ ,  $r > v$  weak. See Fig. 118.  $N_X = 1.525$ ,  $N_Y = 1.534$ ,  $N_Z = 1.552$ ,  $N_Z - N_X = 0.027$  (Larsen <sup>27</sup>);  $N_X = 1.535$ ,  $N_Y = 1.543$ ,  $N_Z = 1.561$ ,  $N_Z - N_X = 0.026$  (Orlov <sup>124</sup>); also  $N_Z = 1.580$ . Color white, yellow, pink, green, brown, black; colorless in section or pleochroic <sup>124</sup> with  $X =$  deep blue to clear green,  $Y =$  brownish yellow,  $Z =$  pale brown to yellow.

OCCUR. Wavellite is found in veins and pegmatites; also in phyllites, as in York County, Pennsylvania.

DIAG. It is characterized by radiated fibrous structure and by its optic properties.

**Overite** <sup>125</sup>  $[Ca_3Al_8(OH)_6(PO_4)_8 \cdot 15H_2O]$  is orthorhombic dipyrnidal with  $a:b:c = 0.786:1:0.380$ . Space group  $Pmam$ ;  $a$  14.75,  $b$  18.74,  $c$  7.12 Å. U.C. 2. Crystals prismatic, flattened on 010, with perfect 010 and poor 100 cleavages.  $H. = 4$ .  $G. = 2.53$ .  $F. = 2$ .  $X = c$ ,  $Y = a$ .  $(- )2V = 75^\circ \pm 10^\circ$ ,  $r > v$  weak.  $N_X = 1.568$ ,  $N_Y = 1.574$ ,  $N_Z = 1.580$ ,  $N_Z - N_X = 0.012$ . Pale green to colorless. Found in phosphate nodules at Fairfield, Utah.

**Bermanite** <sup>126</sup>  $[Mn''_5Mn'''_8(OH)_{10}(PO_4)_8 \cdot 15H_2O]$  is orthorhombic dipyrnidal with  $a:b:c = 0.689:1:2.202$ . Space group  $Pmmm$ ;  $a$  6.25,  $b$  8.92,  $c$  19.61 Å. Crystals show {001}, {111}, {110}, {010}. Perfect 001 and poor 110 cleavages.  $H. = 3.5$ .  $G. = 2.84$ .  $X = c$ ,  $Y = b$ .  $(- )2V = 74^\circ$ ,  $r < v$ .  $N_X = 1.687$ ,  $N_Y = 1.725$ ,  $N_Z = 1.748$ ,  $N_Z - N_X = 0.061$ . Color reddish brown with  $X =$  light red,  $Y =$  pale yellow,  $Z =$  deep red. Found in a vein cutting triplite in pegmatite, near Hillside, Arizona.

**Seamanite** <sup>127</sup>  $(Mn_3B_2O_6 \cdot Mn_3P_2O_8 \cdot 3H_2O)$  is orthorhombic dipyrnidal with  $a:b:c = 0.519:1:0.451$ . Space group <sup>128</sup>  $Pbnm$ ;  $a$  7.83,  $b$  15.14,  $c$  6.71 Å. U.C. 4.

<sup>123</sup> V. Caglioti: *Chem. Abst.*, XXXI, 5290 (1937). W. Jansen: *Zeit. Krist.*, LXXXV, 1 (1933), gives  $a$  7.27,  $b$  14.41,  $c$  10.80 Å.

<sup>124</sup> A. Orlov: *Zeit. Krist.*, LXXVII, 317 (1931). With 3.18  $Fe_2O_3$  and 2.63  $FeO$ .

<sup>125</sup> E. S. Larsen, 3rd: *Am. Mineral.*, XXV, 315 (1940).

<sup>126</sup> C. S. Hurlbut: *Am. Mineral.*, XXI, 656 (1936).

<sup>127</sup> E. H. Kraus, W. A. Seaman, and C. B. Slawson: *Am. Mineral.*, XV, 220 (1930).

<sup>128</sup> D. McConnell: *Am. Mineral.*, XXVI, 446 (1941).

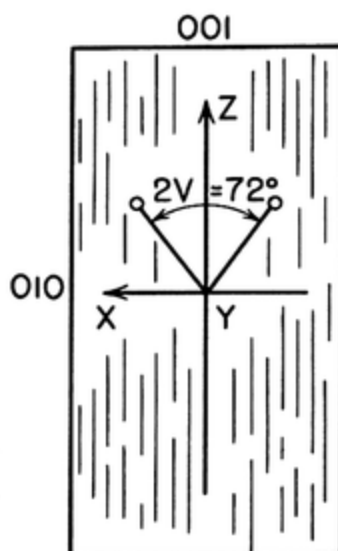


FIG. 118. The optic orientation of wavellite.

Crystals slender prisms ended by pyramids.  $H. = 4$ .  $G. = 3.13$ . Soluble in cold acid. The optic plane is 010;  $Z = c$ .  $(- )2V = 40^\circ \pm$ ,  $r < v$ .  $N_X = 1.640$ ,  $N_Y = 1.663$ ,  $N_Z = 1.665$ ,  $N_Z - N_X = 0.025$ . Color wine yellow. Found in fractures in siliceous rock in Iron County, Michigan.

**Parsonsite**  $(Pb_2UO_2P_2O_8 \cdot H_2O)$  is monoclinic(?) with  $\beta = 99^\circ$ .  $G. = 6.23$ . Fuses to a black globule. Soluble in acid.  $Z \wedge c = 12^\circ$ . Biaxial.  $N_X = 1.85$ ,  $N_Y = ?$ ,  $N_Z = 1.862$ ,  $N_Z - N_X = 0.012$ . Color brown to colorless, the color being due to inclusions. Found in ore in the Congo.

**Beraunite**  $[Fe_6(OH)_6(PO_4)_4 \cdot 5H_2O]$  is monoclinic with  $a:b:c = 2.754:1:4.016$ ,  $\beta = 131^\circ 27'$ . Crystals {100} tablets with distinct 100 cleavage.  $H. = 2$ .  $G. = 2.87-2.98$ . Soluble in HCl. The optic plane is normal to 010;  $X \wedge c = 88.5^\circ$ .  $(+)2V = \text{medium}$ ,  $r > v$  marked;  $N_X = 1.775$ ,  $N_Y = 1.786$ ,  $N_Z = 1.815$ ,  $N_Z - N_X = 0.040$  (Larsen<sup>129</sup>); also: <sup>129</sup>  $Y \wedge c = 5^\circ$ ,  $N = 1.65$ ,  $N_Z - N_X = 0.02 \text{ ca.}$ , and <sup>130</sup>  $N_X = 1.687$ ,  $N_Y > 1.72$ ,  $N_Z < 1.78$ ,  $N_Z - N_X < 0.083$ . Color reddish brown to hyacinth red with  $X = Y = \text{pale flesh color to colorless}$ ,  $Z = \text{carnelian red to vinaceous}$ . Found in iron ore deposits at Giessen, Germany.

**Calcioferite**  $[Ca_3Fe_3(OH)_3(PO_4)_4 \cdot 8H_2O?]$  is monoclinic(?) in scaly nodules with very perfect 001 cleavage.  $H. = 2.5$ .  $G. = 2.53$ .  $F. = \text{easy}$ . Decomposed by HCl. Sensibly uniaxial negative with  $N_O = 1.56-1.58$ ,  $N_O - N_E = \text{weak}$ . Color yellow to green. Found in clay at Battenberg, Bavaria.

**Xanthoxenite**<sup>131</sup>  $[(Ca,Mn,Mg)_2Fe'''(PO_4)_2(OH) \cdot 1.5H_2O]$  is monoclinic or triclinic. Crystals indistinct plates or laths.  $H. = 2.5$ .  $G. = 2.97$ .  $X \wedge \text{length} = 22^\circ$ .  $(-)2V = \text{large}$ ,  $r < v$  strong.  $N_X = 1.704$ ,  $N_Y = 1.715$ ,  $N_Z = 1.724$ ,  $N_Z - N_X = 0.020$ . Color yellow or brownish yellow. Pale yellow in section. A similar mineral from Bavaria has perfect 010 cleavage. Yellow with  $Z > Y$ .  $Z \wedge c = 36^\circ$ ;  $N_Z - N_X = 0.05 \text{ ca.}$  Found at Palermo, New Hampshire.

**Souzalite**<sup>132</sup>  $[(Mg,Fe)_3(Al,Fe)_4(OH)_6(PO_4)_4 \cdot 2H_2O]$  is monoclinic(?); fibrous, with distinct 010 cleavage and twinning on 100.  $G. = 3.087$ .  $X = b$ ,  $Z \text{ near } c$ .  $(-)2V = \text{medium}$  with extreme dispersion.  $N_X \text{ near } 1.623$ ,  $N_Y \text{ near } 1.640$ ,  $N_Z \text{ near } 1.652$ ,  $N_Z - N_X \text{ near } 0.029$ . Color green. Found in pegmatite, as an alteration product of scorzalite, near Divino, Brazil.

**Legrandite**<sup>133</sup>  $[Zn_{14}OH(AsO_4)_9 \cdot 12H_2O]$  is monoclinic with  $a:b:c = 1.608:1:1.289$ ,  $\beta = 104^\circ 25'$ .  $a$  12.70,  $b$  7.90,  $c$  10.18 Å. U.C. 1. Crystals prismatic.  $G. = 4.01$ .  $X = b$ ,  $Z \wedge c = +36^\circ \text{ to } +40^\circ$ .  $(+)2E = 65^\circ \pm 5^\circ$ ,  $r < v$  distinct,  $N_X = 1.675$ ,  $N_Y = 1.690$ ,  $N_Z = 1.735$ ,  $N_Z - N_X = 0.07 \pm$ . Colorless to yellow and pleochroic with  $Y < Z$ . Found with sphalerite at Lampozos, Mexico.

**Roscherite**  $[Ca(Mn,Fe)AlOHP_2O_8 \cdot 2H_2O]$  is monoclinic with  $a:b:c = 0.94:1:0.88$ ,  $\beta = 90^\circ 50'$ . Crystals tabular with perfect 001 and fair 010 cleavages.  $H. = 4.5$ .  $G. = 2.92$ .  $X = b$ ,  $Z \wedge c = -75^\circ$ , with crossed dispersion.  $(-)2V = \text{large}$ ,  $r > v$  very strong.  $N_Y = 1.625$ ,  $N_Z - N_X = \text{rather strong}$ . Color brown with  $X = \text{yellow to olive green}$ ,  $Y = \text{yellowish brown}$ ,  $Z = \text{chestnut brown}$ . Found in pegmatite at Ehrensriedersdorf, Saxony.

**Montgomeryite**<sup>125</sup>  $[Ca_4Al_5(OH)_5(PO_4)_6 \cdot 11H_2O]$  is monoclinic prismatic with  $a:b:c = 0.414:1:0.258$ ,  $\beta = 91^\circ 34'$ . Space group  $C2/c$ ;  $a$  9.99,  $b$  24.10,  $c$  6.25 Å. U.C. 2. Crystals {010} plates with perfect 010 and poor 100 cleavages.  $H. = 4$ .

<sup>129</sup> H. Laubmann and H. Steinmetz: *Zeit. Krist.*, LV, 553 (1920).

<sup>130</sup> S. G. Gordon: *Proc. Acad. Nat. Sci. Phila.*, LXXVII, 1 (1925).

<sup>131</sup> C. Frondel: *Am. Mineral.*, XXXIV, 692 (1949).

<sup>132</sup> W. T. Pecora and J. J. Fahey: *Bull. Geol. Soc. Am.*, LVIII, 1217 (1947).

<sup>133</sup> J. Drugman and M. H. Hey: *Mineral. Mag.*, XXIII, 175 (1932).

G. = 2.53.  $Z = b$ ,  $X \wedge c = -60^\circ$ .  $(-)2V = 75^\circ \pm 10^\circ$ ,  $r < v$  distinct.  $N_X = 1.572$ ,  $N_Y = 1.578$ ,  $N_Z = 1.582$ ,  $N_Z - N_X = 0.010$ . Color deep green to colorless with  $X =$  colorless to pale green,  $Y$  and  $Z =$  colorless. Found in phosphate nodules at Fairfield, Utah.

**Metavauxite**<sup>134</sup>  $[\text{FeAl}_2(\text{OH})_2\text{P}_2\text{O}_8 \cdot 3\text{H}_2\text{O}]$  is monoclinic with  $a:b:c = 1.204:1:0.727$ ,  $\beta = 118^\circ 41'$ . Crystals acicular with vertical striations.  $H. = 3 \pm$ ,  $G. = 2.345$ . The optic plane and  $X$  are normal to 010;  $Z \wedge c = 17^\circ$ .  $(+)2V = 80^\circ$  (calc.),  $N_X = 1.550$ ,  $N_Y = 1.561$ ,  $N_Z = 1.577$ ,  $N_Z - N_X = 0.027$ . Colorless or pale green. Found at Llallagua and Tasna, Bolivia.

**Vauxite**<sup>135</sup>  $[\text{FeAl}_2(\text{OH})_2\text{P}_2\text{O}_8 \cdot 5\text{H}_2\text{O}]$  is triclinic with  $a:b:c = 0.911:1:0.792$ ,  $\alpha = 99^\circ 32'$ ,  $\beta = 110^\circ 14'$ ,  $\gamma = 102^\circ 14'$ . Crystals {001} tablets without known cleavage.  $H. = 3.5$ .  $G. = 2.37$ . Soluble in HCl.  $Z$  nearly normal to 001 in which  $X' \wedge b = +27^\circ$ .  $(+)2V = 32^\circ$ ,  $r > v$ .  $N_X = 1.551$ ,  $N_Y = 1.555$ ,  $N_Z = 1.562$ ,  $N_Z - N_X = 0.011$ . Color sky blue to Venetian blue; streak white. Strongly pleochroic with  $X'$  and  $Z' =$  colorless and  $Y' =$  blue. Found in ore deposits at Llallagua, Bolivia.

**Paravauxite**<sup>136</sup>  $[\text{FeAl}_2(\text{OH})_2\text{P}_2\text{O}_8 \cdot 8\text{H}_2\text{O}]$  is triclinic pinacoidal with  $a:b:c = 0.497:1:0.661$ ,  $\alpha = 107^\circ 16'$ ,  $\beta = 111^\circ 24'$ ,  $\gamma = 72^\circ 29'$ . Unit cell  $a$  5.23,  $b$  10.52,  $c$  6.96 Å. Crystals prismatic with distinct 010 cleavage.  $H. = 3$ .  $G. = 2.29$ . Soluble in HCl. In 010 sections an optic axis is just outside the field; in 100 sections both optic axes are just outside the field. On 010,  $Y' \wedge c = 38^\circ$ , and on 100  $Y' \wedge c = -43^\circ$ .  $(+)2V = 35^\circ$ .  $N_X = 1.554$ ,  $N_Y = 1.558$ ,  $N_Z = 1.573$ ,  $N_Z - N_X = 0.019$ . Colorless. Found in ore deposits at Llallagua, Bolivia.

**Gordonite**<sup>136, 137</sup>  $[\text{MgAl}_2(\text{OH})_2(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}]$  is triclinic pinacoidal with  $a:b:c = 0.498:1:0.663$ ,  $\alpha = 107^\circ 29'$ ,  $\beta = 110^\circ 56'$ ,  $\gamma = 72^\circ 32'$ . Unit cell  $a$  5.22,  $b$  10.49,  $c$  6.95 Å. Perfect 010 and fair 100 cleavages.  $H. = 3.5$ .  $G. = 2.23$ .  $F. = 3$ . Soluble in acids.  $X$  nearly normal to 100;  $Z' \wedge c = +26^\circ$  in 100.  $(+)2V = 73^\circ$ ,  $r > v$  perceptible.  $N_X = 1.534$ ,  $N_Y = 1.543$ ,  $N_Z = 1.558$ ,  $N_Z - N_X = 0.024$ . Colorless and glassy clear. Found in nodules at Fairfield, Utah.

**Planerite**  $[\text{Al}_6(\text{OH})_6(\text{PO}_4)_4 \cdot 15\text{H}_2\text{O}]$  is apparently amorphous.  $H. = 2.5$ .  $G. = 2.65$ . Isotropic with  $N = 1.517$ . Also in part birefringent. Color green. Chemically closely related to ceruleolactite. Found in copper ores in the Urals.

### 3. Phosphates with type formula $\approx A_2BX_4$

#### (a) WITHOUT ADDITIONAL ANIONS—ANHYDROUS

**TRIPHYLITE(-Lithiophilite)** ORTHORHOMBIC DIPYRAMIDAL  $\text{Li}(\text{Fe}, \text{Mn})\text{PO}_4$   
 $a:b:c = 0.454:1:0.583$

COMP. Mg may proxy for (Fe, Mn);  $\text{Na}_2\text{O}$  may be present.

STRUC. Space group <sup>138</sup>  $Pnma$ ;  $a$  4.71,  $b$  10.37,  $c$  6.04 Å. U.C. 4.

<sup>134</sup> S. G. Gordon: *Proc. Acad. Nat. Sci. Phila.*, XCVI, 279 (1944).

<sup>135</sup> S. G. Gordon: *Proc. Acad. Sci. Phila.*, LXXV, 261 (1923); *Science*, LVI, 50 (1922).  $abc$  changed to  $acb$  to make  $b > a > c$ .

<sup>136</sup> E. W. Nuffield: *Bull. Geol. Soc. Am.*, LVII, 1220 (1946).

<sup>137</sup> E. S. Larsen and E. V. Shannon: *Am. Mineral.*, XV, 307 (1930). F. H. Pough: *Am. Mineral.*, XXII, 625 (1937). See also E. S. Larsen: *Am. Mineral.*, XXVII, 281 (1942).

<sup>138</sup> C. O. Björling and A. Westgren: *Geol. För. Förh. Stockholm*, LX, 67 (1938).

PHYS. CHAR. Crystals prismatic with perfect 001 and good 010 and 110 cleavages. H. = 5. G. = 3.4–3.6. F. = 1.5–2. Soluble in HCl.

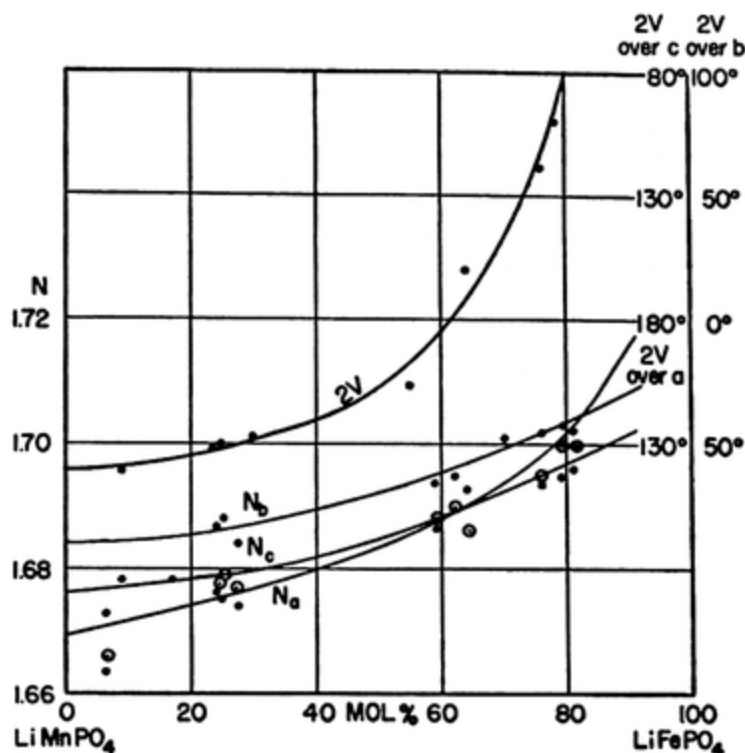


FIG. 119. Properties of triphylite(-lithiophilite) See C. A. Chapman: *Am. Mineral.*, XXVIII, 90 (1943).

OPT. PROP. The properties vary with the variations in tenor of iron as shown in Fig. 119 and in the following table:

Color	Mol. % LiFePO <sub>4</sub>	N <sub>X</sub>	N <sub>Y</sub>	N <sub>Z</sub>	N <sub>Z</sub> - N <sub>X</sub>	2V over b	Orientation	G.
	81	1.696	1.700	1.702	0.006			3.552
Light gray	77		1.702 Na			(-)120°, r < 9	X = c, Y = a	3.55
Light gray	74	1.695	1.701	1.703	0.008	(-)80°, r < 9	X = c, Y = a	
Light gray	70	1.694	1.695	1.702	0.008	(+)62°, r > 9	X = c, Y = a	
Brown	64	1.686	1.687	1.693	0.007	(+)20°, r > 9	X = c, Y = a	
Light blue	58.5	1.683 Li	1.684 Li	1.691 Li	0.008 Li	(+)15° 3' Li	X = c, Y = a	
		1.688 Na	1.688 Na	1.692 Na	0.004 Na	(+)0° 0' Na	Z = b	
		1.691 Tl	1.692 Tl	1.698 Tl	0.007 Tl	(+)21° 53' Tl	X = a, Y = c	
Light clove brown	{ 30 25		1.682 Na			(+)56° 4' Na	X = a	
		1.676 Na	1.679 Na	1.687 Na	0.011 Na	(+)62° 54' Na	Y = c	
Salmon pink	{ 9 6		1.675 Na			(+)65° 13' Na	X = a	
		1.663	1.666	1.673	0.010	(+) 7 r < 9	Y = c	3.5

These variations are shown <sup>120</sup> in Fig. 119 from which it appears that the optic plane is probably 010 in pure iron triphylite, the index in the direction of *a* changing from the least to the greatest and the mineral passing through the uniaxial condition twice with variations in composition. Also, it appears that the Mn:Fe ratio is

<sup>120</sup> The curvature of the index lines in the figure may be due to the fact that variations in tenor of Mg are disregarded.

given approximately by the measurement of the optic angle, and the proportion of Mg may be estimated by noting that about 27 mol. per cent of MgO lowers the indices about 0.025, as shown by Chapman.<sup>140</sup>

Color greenish gray or bluish or brown with excess of Fe, salmon pink, yellow, or brown with excess of Mn; often black on the surface. Lithiophilite may be pleochroic with X = deep pink, Y = pale greenish yellow, Z = pale pink.

**ALTER.** Triphylite oxidizes and hydrates very readily to heterosite, hureaulite, dufrenite, etc., turning brown, red, or black, and developing three good cleavages. Ultimately pyrolusite and limonite may form.

**OCCUR.** Triphylite is found in pegmatites associated with apatite, beryl, tourmaline, lepidolite, amblygonite, spodumene, etc., as at Rabenstein, Bavaria; Branchville, Connecticut, etc.

**Natrophilite** ( $NaMnPO_4$ ) is orthorhombic dipyramidal<sup>141</sup> with  $a:b:c = 0.472:1:0.55$ . Space group  $Pnma$ ;  $a$  6.32,  $b$  10.52,  $c$  4.97. U.C. 4. Perfect 001 and good 010 cleavages.  $H. = 4.5-5$ .  $G. = 3.4$ .  $F. = 2-2.5$ . Soluble in acid. The optic plane is 001;  $Z = b$ .  $(+ )2V = 72^\circ$ ,  $r < v$  strong.  $N_X = 1.671$ ,  $N_Y = 1.674$ ,  $N_Z = 1.684$ ,  $N_Z - N_X = 0.013$ . Color deep wine yellow. Found in pegmatite at Branchville, Connecticut.

**Varulite**<sup>142</sup> [ $Na(Mn,Fe)PO_4$ ] is orthorhombic, similar to triphylite. The iron is often partly oxidized, apparently with loss of sodium. Good 001 and 010 cleavages.  $G. = 3.58$ . The optic plane is 010.  $(- )2V = 70^\circ$ ,  $r > v$  distinct.  $N_X = 1.720$ ,  $N_Y = 1.728$  calc.,<sup>142</sup>  $N_Z = 1.732$ ,  $N_Z - N_X = 0.012$ . Color dull olive green; colorless in thin section. Found at Varuträsk, Sweden.

**Beryllonite** ( $NaBePO_4$ ) is monoclinic<sup>143</sup> with  $a:b:c = 1.043:1:1.822$ ,  $\beta = 90^\circ \pm$ . Very nearly orthorhombic. Space group  $P2_1/c$ ;  $a$  8.13,  $b$  7.76,  $c$  14.17 Å. U.C. 12. Twinning makes pseudohexagonal forms. Perfect 010, good 100, and poor 001 cleavages.  $H. = 6$ .  $G. = 2.85$ .  $F. = 5$ . Soluble in acid. The optic plane is 100;  $X = b$ .  $(- )2V = 67^\circ 34'$ ,  $r < v$  weak.  $N_X = 1.552$  Na,  $N_Y = 1.558$ ,  $N_Z = 1.561$ ,  $N_Z - N_X = 0.009$ . Colorless to yellowish. Cavities, with or without inclusions, are numerous; they may be arranged parallel to the  $b$  axis. Found at Stoneham, Maine.

**Schultenite**<sup>144</sup> ( $HPbAsO_4$ ) is monoclinic with  $a:b:c = 0.864:1:0.718$ ,  $\beta = 95^\circ 24'$ . Crystals {010} tablets, with distinct 010 cleavage.  $H. = 2.5$ .  $G. = 5.94$  (Spencer), 6.08 (Schulten).  $Y = b$ ; extinction at  $+38^\circ$  to  $a$  in 010 (Schulten).  $X = b$ ;  $Z \wedge c = -66^\circ$  (Spencer).  $(+ )2V = 58^\circ$ ,  $N_X = 1.890$ ,  $N_Y = 1.910$ ,  $N_Z = 1.977$  (calc.),  $N_Z - N_X = 0.087$ . Colorless. This is the lead arsenate of commerce. Found at Tsumeb, South Africa.

<sup>140</sup> C. A. Chapman: *Am. Mineral.*, XXVIII, 90 (1943).

<sup>141</sup> A. Byström: *Arkiv Kemi, Min. Geol.*, XVIIB, No. 4 (1943).  $abc$  changed to  $bca$  to make  $b > a > c$ .

<sup>142</sup> P. Quensel: *Geol. För. Förh.*, LIX, 93 (1937): Optic sign from personal communication, Nov. 16, 1938. Called arrojadite if  $Fe > Mn$ : B. Mason: *Geol. För. Förh.*, LXIII, 117 (1941). With only 9.79 MnO,  $N_X = 1.718$ ,  $N_Z = 1.731$ . See T. Eriksson: *Arkiv. Kemi*, XXIIIA, No. 8 (1946). With  $Fe_2O_3$  none,  $FeO$  28.22,  $MnO$  15.78,  $Na_2O$  6.40, etc.  $(- )2V = 86^\circ$ ,  $r < v$  strong,  $N_X = 1.664$ ,  $N_Y = 1.670$ ,  $N_Z = 1.675$ ,  $N_Z - N_X = 0.011$ . See M. L. Lindberg: *Geol. Soc. Am., Bull.*, LIX, 1336 (1948).

<sup>143</sup> B. Gossner and J. Besslein: *Cent. Mineral.*, 1934A, 144.

<sup>144</sup> L. J. Spencer: *Mineral. Mag.*, XXI, 149 (1926). A. de Schulten: *Bull. Soc. Fr. Min.*, XXVII, 109 (1904).



**Monetite** <sup>145</sup> ( $\text{HCaPO}_4$ ) is triclinic pinacoidal with  $a:b:c = 0.647:1:0.824$ ,  $\alpha = 84^\circ 57'$ ,  $\beta = 90^\circ 17'$ ,  $\gamma = 94^\circ 22'$ . Crystals thin {010} plates or {10 $\bar{1}$ } plates elongated parallel to the edge 10 $\bar{1}$ :011. Distinct 001 and 110 cleavages.  $H. = 3.5$ .  $G. = 2.93$ .  $F. = 3$ . Soluble in acid. The optic plane is nearly parallel with 010.  $(- )2V = \text{large}$ ,  $r > v$ .  $N_X = 1.600$ ,  $N_Y = 1.614$ ,  $N_Z = 1.631$ ,  $N_Z - N_X = 0.031$  (Berman <sup>61</sup>);  $N_X = 1.587$ ,  $N_Y = 1.615$ ,  $N_Z = 1.640$ ,  $N_Z - N_X = 0.053$  (Hill <sup>146</sup>). Colorless. Found beneath guano in limestone on Moneta Island, West Indies.

### (a) WITHOUT ADDITIONAL ANIONS—HYDROUS

**Haidingerite** ( $\text{HCaAsO}_4 \cdot \text{H}_2\text{O}$ ) is orthorhombic dipyramidal with  $a:b:c = 0.427:1:0.493$ ; perfect 010 and good other cleavages giving {010} tablets with angles of  $33^\circ$  and  $147^\circ$ .  $H. = 2$ .  $G. = 2.85$ ;  $2.97$ .  $F. = 2.5$ . Soluble in  $\text{HNO}_3$ . The optic plane is 100;  $Z = c$ .  $(+)2V = 58^\circ$ . Dispersion slight.  $N_X = 1.590$ ,  $N_Y = 1.602$ ,  $N_Z = 1.638$ ,  $N_Z - N_X = 0.048$ . Colorless. Found with pharmacolite at Joachimstal, Bohemia.

**Newberyite** ( $\text{HMgPO}_4 \cdot 3\text{H}_2\text{O}$ ) is orthorhombic dipyramidal with  $a:b:c = 0.955:1:0.936$ . Crystals {100} tablets with perfect 010 and poor 001 cleavages.  $H. = 3$ .  $G. = 2.1$  (Larsen <sup>27</sup>);  $2.30$  (Richards <sup>147</sup>). Soluble in  $\text{HNO}_3$ . The optic plane is 010;  $Z = c$ .  $(+)2V = 44^\circ 47'$ ,  $r < v$ .  $N_X = 1.514$ ,  $N_Y = 1.517$ ,  $N_Z = 1.533$ ,  $N_Z - N_X = 0.019$ . Again: <sup>147</sup>  $(+)2V = 35^\circ$ ,  $N_X = 1.517$ ,  $N_Y = 1.520$ ,  $N_Z = 1.531$ ,  $N_Z - N_X = 0.014$ . Color white. Found in guano, as near Ballarat, Victoria.

**Struvite** <sup>148</sup> ( $\text{NH}_4\text{MgPO}_4 \cdot 6\text{H}_2\text{O}$ ) is orthorhombic pyramidal with <sup>149</sup>  $a:b:c = 0.630:1:0.553$ . Space group <sup>150</sup>  $Pmn$ .  $a$  7.00,  $b$  11.11,  $c$  6.14 Å. U.C. 2. Crystals hemimorphic, prismatic, etc. Twinning on 001. Perfect 001 and good 010 cleavages.  $H. = 2$ .  $G. = 1.715$ .  $F. = 3$ . Soluble in acids. The optic plane is 001;  $Z = b$ .  $(+)2V = 37^\circ$ ,  $r < v$  strong.  $N_X = 1.4954$ ,  $N_Y = 1.4963$ ,  $N_Z = 1.5043$ ,  $N_Z - N_X = 0.0089$ . Colorless or yellow. Found in guano, as near Ballarat, Victoria.

**Dickinsonite** [ $\text{H}_2\text{Na}_6\text{Mn}_{14}(\text{PO}_4)_{12} \cdot \text{H}_2\text{O}$ ] is monoclinic prismatic <sup>151</sup> with  $a:b:c = 1.678:1:2.481$ ,  $\beta = 104^\circ 41'$ . Space group  $C2/c$ .  $a$  16.70,  $b$  9.95,  $c$  24.69 Å. U.C. 4. Crystals basal tablets with perfect basal cleavage.  $H. = 3.5-4$ .  $G. = 3.34-3.41$ .  $F. = 2.5-3$ . Soluble in acid.  $X = b$ ;  $Y$  nearly normal to 001.  $(+)2V = \text{medium}$ ,  $r > v$  strong.  $N_X = 1.658$ ,  $N_Y = 1.662$ ,  $N_Z = 1.671$ ,  $N_Z - N_X = 0.013$ . A sample <sup>45</sup> from Poland, Maine, has  $(+)2V = \text{nearly } 90^\circ$ ,  $N_X = 1.648$ ,  $N_Y = 1.655$ ,  $N_Z = 1.662$ ,  $N_Z - N_X = 0.014$ . Color olive-green; absorption  $X > Y > Z$ . Found in pegmatite at Branchville, Connecticut.

**Pharmacolite** ( $\text{HCaAsO}_4 \cdot 2\text{H}_2\text{O}$ ) is monoclinic prismatic with  $a:b:c = 0.623:1:0.355$ ,  $\beta = 96^\circ 47'$ . <sup>152</sup>  $a$  10.97,  $b$  15.40,  $c$  6.29 Å. U.C. 8. Crystals {010} tablets or fibrous. Perfect 010 cleavage.  $H. = 2$ .  $G. = 2.7$ .  $F. = 2.5$ , with intumescence. Soluble in acid.  $Z = b$ ;  $X \wedge c = -70^\circ$ .  $(-)2V = 79^\circ 24'$  Na,  $r < v$  distinct.  $N_X = 1.5825$  Na,  $N_Y = 1.5891$ ,  $N_Z = 1.5937$ ,  $N_Z - N_X = 0.0112$ . Color white

<sup>145</sup> P. Groth: *Chem. Kryst.*, II, 820 (1908).

<sup>146</sup> W. H. Hill and S. B. Hendricks: *Ind. Eng. Chem.*, XXVIII, 440 (1936).

<sup>147</sup> G. Richards: *Am. Mineral.*, XIII, 397 (1928).

<sup>148</sup> O. B. Böggild: *Med. Dansk. geol. För.*, No. 13 (1907).

<sup>149</sup> R. Salvia: *Brit. Chem. Abst.*, 1935A, 434.  $abc$  changed to  $acb$  to make  $b > a > c$ .

<sup>150</sup> J. Garrido: *Chem. Abst.*, XLI, 59 (1947).

<sup>151</sup> C. W. Wolfe: *Am. Mineral.*, XXVI, 338 (1941).

<sup>152</sup> B. Gossner: *Zeit. Krist.*, XCVI, 488 (1937).



or stained. Found with Co and Ag ores and with arsenopyrite, as at Wittichen, Baden.

**Brushite** ( $\text{HCaPO}_4 \cdot 2\text{H}_2\text{O}$ ) is monoclinic sphenoidal<sup>153</sup> with  $a:b:c = 0.682:1:0.416$ ,  $\beta = 95^\circ 7'$ . Space group  $C2$ .  $a$  10.3,  $b$  15.4,  $c$  6.4 Å. Crystals {010} plates or fibrous, with perfect 010 and 301 cleavages.  $H. = 2$ .  $G. = 2.25\text{--}2.33$ .  $F. = 3$ , with intumescence. Soluble in dilute acid.  $Z = b$ ;  $X \wedge c$ <sup>153</sup> =  $+10.5^\circ \text{Na}$ ,  $9.2^\circ \text{Li}$ ,  $11.2^\circ \text{Ti}$ ; again:<sup>154</sup>  $X \wedge c = +13^\circ$ .  $(+ )2V = 86^\circ$ ,  $r > v$ , with distinct crossed dispersion.  $N_X = 1.542$ ,  $N_Y = 1.548$ ,  $N_Z = ?$ ; again,  $(- )2V = \text{very large}$ ,  $N_X = 1.5392$ ,  $N_Y = 1.5455$ ,  $N_Z = 1.5509$ ,  $N_Z - N_X = 0.0117$ ; also<sup>155</sup>  $N_Z = 1.5412$ ,  $N_Y = 1.5458$ ,  $N_Z = 1.553$ ,  $N_Z - N_X = 0.0118$ . Color pale yellow to white. Alters to monelite when heated in balsam. Found on rock guano on Aves Island, West Indies.

**Palaite** [ $\text{H}_2\text{Mn}_5(\text{PO}_4)_4 \cdot 3\text{H}_2\text{O}$ ] is monoclinic.  $G. = 3.2$ .  $F. = \text{easy}$ . Soluble in acid.  $(- )2V = \text{large}$ , with weak dispersion.  $N_X = 1.652$ ,  $N_Y = 1.656$ ,  $N_Z = 1.660$ ,  $N_Z - N_X = 0.008$ . Flesh-colored. Derived from alteration of lithiophilite and alters to hureaulite.

**Phosphorösslerite** ( $\text{HMgPO}_4 \cdot 7\text{H}_2\text{O}$ ) is monoclinic prismatic<sup>156</sup> with  $a:b:c = 0.446:1:0.260$ ,  $\beta = 94^\circ 56'$ . Space group  $C2/c$ ;  $a$  11.35,  $b$  25.36,  $c$  6.60 Å. U.C. 8. Crystals show {011}, {010}, {110}, etc. No cleavage observed.  $H. = 2.5$ .  $G. = 1.725$ .  $X = b$ ;  $Z \wedge c = +6.5^\circ$ .  $(- )2V = 39^\circ 10'$  red,  $37^\circ 20'$  blue,  $N_X = 1.477$ ,  $N_Y = 1.485$ ,  $N_Z = 1.486$ ,  $N_Z - N_X = 0.011$ . Related to wapplerite. Found in Salzburg, Germany.

**Rösslerite** ( $\text{HMgAsO}_4 \cdot 7\text{H}_2\text{O}$ ) is monoclinic prismatic with  $a:b:c = 0.447:1:0.260$ ,  $\beta = 94^\circ 26'$ .  $X = b$ ;  $Z \wedge c = +14^\circ$ ?  $(- )2V = \text{small}$ .

**Hureaulite** [ $\text{H}_2\text{Mn}_5(\text{PO}_4)_4 \cdot 4\text{H}_2\text{O}$ ] is monoclinic prismatic<sup>156</sup> with  $a:b:c = 1.931:1:1.047$ ,  $\beta = 96^\circ 40'$ . Space group  $P2/c$ ;  $a$  17.42,  $b$  9.12,  $c$  9.50 Å U.C. 4. Crystals short prismatic or {100} tablets, with distinct 100 cleavage.  $H. = 3\text{--}4$ .  $G. = 3.18$ .  $F. = 3$ . Soluble in acid.  $X = b$ ;  $Z \wedge c = -75^\circ$ .  $(- )2V = 74^\circ$ ,  $r < v$  very strong, with strong crossed dispersion.  $N_X = 1.647$ ,  $N_Y = 1.654$ ,  $N_Z = 1.660$ ,  $N_Z - N_X = 0.013$ . The optic angle decreases  $6.5^\circ$  on heating from  $41^\circ \text{C}$ . to  $121^\circ \text{C}$ . Color orange-red, rose-violet, pink, grayish. Orange-red type pleochroic with  $X = \text{colorless}$ ,  $Y = \text{clear yellow to pale rose}$ ,  $Z = \text{reddish yellow to reddish brown}$ . Found in pegmatite at Hureaux, France; Branchville, Connecticut; and Pala, California.

**Wapplerite** ( $\text{HCaAsO}_4 \cdot 3.5\text{H}_2\text{O}$ ) is triclinic(?) with  $a:b:c = 0.901:1:0.262$ ,  $\alpha = 90^\circ 14'$ ,  $\beta = 95^\circ 20'$ ,  $\gamma = 90^\circ 11'$ . Crystals equant with perfect 010 cleavage.  $H. = 2\text{--}2.5$ .  $G. = 2.48$ .  $Z$  nearly  $= b$ ; extinction angle on 010 =  $20^\circ$ .  $(+ )2V = 35^\circ$ ,  $r < v$  with perceptible crossed dispersion.  $N_X = 1.525$ ,  $N_Y = 1.53$ ,  $N_Z = 1.550$ ,  $N_Z - N_X = 0.025$ . Colorless. Found with pharmacolite at Schneeberg, Saxony.

**Hannayite** [ $\text{H}_4(\text{NH}_4)_2\text{Mg}_3(\text{PO}_4)_4 \cdot 8\text{H}_2\text{O}$ ] is triclinic pinacoidal with  $a:b:c = 0.699:1:0.975$ ,  $\alpha = 122^\circ 31'$ ,  $\beta = 126^\circ 46'$ ,  $\gamma = 54^\circ 9'$ . Crystals platy or prismatic with cleavages parallel to 001, 110,  $1\bar{1}0$ , and 130. Soft.  $G. = 1.89$ . Optically it seems to be monoclinic (Larsen<sup>27</sup>) with  $X = b$  (normal to perfect 010 cleavage)<sup>157</sup> and  $Z \wedge c$  (elongation) =  $57^\circ$ .  $(- )2V = 42^\circ$ , with weak dispersion.  $N_X = 1.555$ ,

<sup>153</sup> P. Terpstra: *Zeit. Krist.*, XCVII, 229 (1937).

<sup>154</sup> J. Mélon and M. J. Dallemagne: *Chem. Abst.*, XL, 6315 (1946); *Min. Abst.*, X, 110 (1947).

<sup>155</sup> O. M. Friedrich and J. Robitsch: *Cent. Mineral.*, 1939A, 142.

<sup>156</sup> J. Murdoch: *Am. Mineral.*, XXVIII, 19 (1943).

<sup>157</sup> This is the 001 cleavage in the triclinic orientation.

$N_Y = 1.572$ ,  $N_Z = 1.575$ ,  $N_Z - N_X = 0.020$ . Color yellowish. Found in bat guano near Ballarat, Victoria.

### (b) WITH ADDITIONAL ANIONS—ANHYDROUS

**Griphite**  $[(Na, Al, Ca, Fe)_6 Mn_4 (OH)_4 (PO_4)_6]$  is isometric<sup>158</sup> (hexoctahedral?) with  $a$  12.26 Å. U.C. 4.  $H. = 5.5$ .  $G. = 3.40$ .  $F. = \text{easy}$ . Soluble in HCl. Isotropic with  $N = 1.64$ – $1.66$ . Color brown. Closely related in structure to garnet. Found in tin ore in South Dakota.

**Florencite**  $[Al(OH)_2]_3 CeP_2O_8$  is hexagonal with  $c/a = 1.159$ ; related to hamlinite and alunite. Crystals rhombohedral, with good basal cleavage.  $H. = 5$ .  $G. = 3.59$ .  $F. = 7$ . Partly soluble in HCl. Uniaxial positive with  $N_O = 1.680 \pm$ ,  $N_E = 1.685$ ,  $N_E - N_O = 0.005 \pm$ . Color brown, yellow, red. Found in schists and placers in Brazil. *Stiepelmannite* is a variety of florencite<sup>159</sup> containing Ce, La, and Pr; it has  $N_O = 1.695$ ,  $N_E = 1.705$ ,  $N_E - N_O = 0.010$ .

**Arseniopleite**  $[(Mn, Ca, Pb)_9 (Mn''', Fe''')_2 (OH)_6 (AsO_4)_6]$  is hexagonal with rhombohedral cleavage.  $H. = 3.5$ . Fuses easily to a black bead. Soluble in HCl. Uniaxial positive with  $N_O = 1.794$ ,  $N_E = 1.803$ ,  $N_E - N_O = 0.009$ . Some crystals slightly biaxial. Color brownish red; blood red and not pleochroic in section. Found in ore deposits in Sweden.

#### OLIVENITE

ORTHORHOMBIC DISPHENOIDAL(?)



$$a:b:c = 0.948:1:0.681$$

STRUC.<sup>160</sup> Space group  $P2_12_12_1(?)$ ;  $a$  8.16,  $b$  8.54,  $c$  5.86 Å. U.C. 4.

PHYS. CHAR. Crystals {100} tablets elongated along  $c$ , equant, or elongated along  $a$ ; difficult 110 and 011 cleavages.  $H. = 3$ .  $G. = 4.1$ – $4.4$ .  $F. = 2$ – $2.5$ . Soluble in HCl.

OPT. PROP. The optic plane is 001;  $X = a$ .

	Cornwall <sup>27</sup>	Utah <sup>161</sup>	Chile <sup>162</sup>
(+)2V =	90° ±	82° $r < v$	Near 90° $r < v$
		strong	strong
$N_X =$	1.747	1.772	1.780
$N_Y =$	1.785–1.795	1.810	1.820
$N_Z =$	1.829	1.863	1.865
$N_Z - N_X =$	0.082	0.091	0.085

Color green to dark brown or yellow. Not pleochroic; or weakly so with  $X = \text{pale greenish}$ ,  $Y = \text{yellowish to greenish}$ ,  $Z = \text{pale greenish to yellow}$ .

OCCUR. Found in the oxide zone of copper deposits in crystals or in fibrous masses known as *wood-copper*, as in Cornwall, Tyrol, Chile, Utah.

<sup>158</sup> D. McConnell: *Am. Mineral.*, XXVII, 452 (1942).

<sup>159</sup> E. R. Ygberg: *Ark. Kemi, Min. Geol.*, 20 A, No. 4 (1945).

<sup>160</sup> H. Heritsch: *Zeit. Krist.*, XCIX, 466 (1938); W. E. Richmond: *Am. Mineral.*, XXV, 441 (1940).

<sup>161</sup> O. C. Farrington and E. W. Tillotson: *Field Col. Mus. Geol. Ser.*, III, 7, 152 (1908).

<sup>162</sup> O. W. Jarrell: *Am. Mineral.*, XXIV, 632 (1939).

**Libethenite** ( $Cu_2OHPO_4$ ) is orthorhombic dipyramidal with  $a:b:c = 0.960:1:0.703$ . Space group <sup>163</sup>  $Pnnm$ ;  $a$  8.08,  $b$  8.43,  $c$  5.90 Å. U.C. 4. Crystals equant, with poor 100 and 010 cleavages.  $H. = 4$ .  $G. = 3.7$ .  $F. = 2-2.5$ . Soluble in acid. The optic plane <sup>164</sup> is 001;  $X = b$ .  $(- )2V = 81-85^\circ$ ;  $r > v$  strong.  $N_X = 1.702$ ,  $N_Y = 1.745$ ,  $N_Z = 1.789$ ,  $N_Z - N_X = 0.087$ . Color olive green, with  $X =$  pale green to yellow or bluish,  $Y =$  bright green to yellowish green,  $Z =$  pale green to yellow or bluish; also pale green and not pleochroic. Often shows spots of different color. Found in the oxide zone of some copper deposits, as at Libethen, Hungary.

**Adamite** ( $Zn_2OHAsO_4$ ) is orthorhombic dipyramidal with  $a:b:c = 0.975:1:0.705$ . May contain Cu, Ca, Fe. Space group <sup>165</sup>  $Pnnm$ ;  $a$  8.32,  $b$  8.54,  $c$  6.08 Å. U.C. 4. Crystals may be elongated along  $b$ ; with 101 cleavage.  $H. = 3.5$ .  $G. = 4.35$ .  $F. = 3$ . Soluble in HCl. The optic plane is 001;  $X = a$ .  $(+ )2V = 83^\circ$ ,  $r < v$  strong.  $N_Y = 1.728$ ; also  $(- )2V = 90^\circ$  *ca.*,  $r > v$  strong,  $N_X = 1.708$ ,  $N_Y = 1.734$ ,  $N_Z = 1.758$ ,  $N_Z - N_X = 0.050$  (Larsen <sup>27</sup>); again  $(+ )2V = 90^\circ$ ,  $N_X = 1.720$ ,  $N_Y = 1.740$ ,  $N_Z > 1.745$  (Murdoch <sup>166</sup>); and  $N_X = 1.742$ ,  $N_Y = 1.768$ ,  $N_Z = 1.773$ ,  $N_Z - N_X = 0.031$  (Tsumeb). Color yellow, green, pink, white. Colorless in section or pleochroic with maximum absorption parallel to  $X$ ; in pink types  $X =$  carmine. A sea-green type from Tsumeb contains copper. Pink types contain cobalt up to 5 per cent. Also  $X =$  rose,  $Y =$  yellowish brown,  $Z =$  yellow; again  $X =$  magenta,  $Y =$  purple,  $Z =$  rose. Found in the oxide zone of zinc deposits, as at Laurium, Greece and Mapimi, Mexico.

<b>DESCLOIZITE</b>	ORTHORHOMBIC DIPYRAMIDAL	$PbZnOHVO_4$
<b>MOTTRAMITE</b>	$a:b:c = 0.805:1:0.643$	$PbCuOHVO_4$

COMP. There is a continuous series <sup>167</sup> from  $PbZnOHVO_4$  to  $PbCuOHVO_4$ ; an intermediate type has been called *cuprodescloizite*.

STRUC. <sup>167</sup> Space group  $Pmcn$ ; for descloizite,  $a$  7.56,  $b$  9.39,  $c$  6.05 Å.; nearly the same for mottramite. U.C. 4.

PHYS. CHAR. Crystals often pyramidal, with poor or no cleavage.  $H. = 3.5$ .  $G. = 5.9-6.2$ .  $F. = 1.5$ . Soluble in dilute  $HNO_3$ .

OPT. PROP. The optic plane is 010;  $X = a$ .

Descloizite	Cuprodescloizite	Mottramite
$(+ )2V =$ large $r < v$ strong	$(- )2V = 50-70^\circ$ $r > v$ strong	? $r > v$ strong
$N_X = 2.185$ pale yellow	2.17-2.21 colorless	2.22 <i>ca.</i> olive green
$N_Y = 2.265$ greenish yellow	2.26-2.31 red-brown	? olive green
$N_Z = 2.35$ dark golden yellow	2.33 red-brown	2.33 <i>ca.</i> olive green
$N_Z - N_X = 0.165$	0.12-0.15	0.11 <i>ca.</i>

<sup>163</sup> H. Heritsch: *Zeit. Krist.*, CCII, 1 (1939); W. E. Richmond: *Am. Mineral.*, XXV, 441 (1940).

<sup>164</sup> Extinction angles up to  $20^\circ$  or more reported by J. J. Glass: *Am. Mineral.*, XXXII, 577 (1947).

<sup>165</sup> P. Kokkoros: *Zeit. Krist.*, XCVI, 417 (1937); W. E. Richmond: *Am. Mineral.*, XXV, 441 (1940); M. E. Mrose: *Am. Mineral.*, XXXIII, 449 (1948).

<sup>166</sup> J. Murdoch: *Am. Mineral.*, XXI, 811 (1936).

<sup>167</sup> F. A. Bannister: *Mineral. Mag.*, XXIII, 376 (1933); W. E. Richmond: *Am. Mineral.*, XXV, 441 (1940).

**OCCUR.** Found in the oxide zone of some ore deposits.

**Pyrobelonite** ( $\text{PbMnOHVO}_4$ ) is orthorhombic dipyramidal with  $a:b:c = 0.802:1:0.644$ . Space group  $^{168} Pnam$ ;  $a$  7.84,  $b$  9.45,  $c$  6.09 Å. U.C. 4. May have Pb:Mn = 5:3. Crystals small acicular. H. = 3.5. G. = 5.38. The optic plane is 001;  $X = a$ .  $(- )2V =$  moderate,  $N_X = 2.32$ ,  $N_Y = 2.36$ ,  $N_Z = 2.37$ ,  $N_Z - N_X = 0.05$ . Found in ores at Långban, Sweden.

**Adelite** ( $\text{CaMgOHAsO}_4$ ) is orthorhombic dipyramidal  $^{169}$  with  $a:b:c = 0.840:1:0.665$ .  $a$  7.43,  $b$  8.85,  $c$  5.88 Å. U.C. 4. Crystals basal tablets or prismatic, without cleavage. H. = 5. G. = 3.75. F. = easy. Soluble in  $\text{HNO}_3$ . The optic plane is 100;  $Z = b$ .  $(+ )2V = 70^\circ \pm$ ,  $r < v$ .  $N_X = 1.712$ ,  $N_Y = 1.721$ ,  $N_Z = 1.731$ ,  $N_Z - N_X = 0.019$ . Color gray. Found in manganese-ore deposits at Jakobsberg, Sweden.

**Volborthite** ( $\text{CuCaOHVO}_4$ ) is orthorhombic  $^{170}$  dipyramidal, much like adelite. It may vary considerably in composition—Ca may exceed Cu (*calciovolborthite*); Ba may proxy for part of the Ca; or As may proxy for part of the V, in which case it is greenish yellow. Crystals six-sided tablets with one perfect cleavage. H. = 3–3.5. G. = 3.5–3.9. F. = 1.5–3.  $X$  or  $Z$  nearly normal to plates.  $(\pm)2V =$  large to small,  $r > v$  very strong.

	Volborthite with Ba	With $\text{As}_2\text{O}_5$	Calciovolborthite
$2V =$	$\pm$ Large to small		$(+ )68^\circ \text{ Li, } 83^\circ \text{ Na, } 89^\circ \text{ Ti}$
$N_X =$	2.00		2.01
$N_Y =$	2.01	$N = 1.92$	2.05
$N_Z =$	2.02		2.10
$N_Z - N_X =$	0.02	?	0.09
Color =	Olive green to lemon yellow	Greenish yellow	Yellowish green

Found in mines in the Urals and on sandstone in Utah.

**Higginsite** ( $\text{CaCuOHAsO}_4$ ) is orthorhombic  $^{170}$  dipyramidal with  $a:b:c = 0.806:1:0.636$ ; space group  $Pmam$ ;  $a$  7.42,  $b$  9.20,  $c$  5.85 Å. U.C. 4. Crystals prismatic or domatic. H. = 4.5. G. = 4.33. F. = 3. Soluble in acid. The optic plane is 100;  $X = b$ .  $(- )2V =$  nearly  $90^\circ$ ,  $r > v$  rather strong.  $N_X = 1.800$ ,  $N_Y = 1.831$ ,  $N_Z = 1.846$ ,  $N_Z - N_X = 0.046$ . Again:  $(- )2V = 25^\circ$ ,  $N_X = 1.778$ ,  $N_Y = 1.78$ ,  $N_Z = 1.801$ ,  $N_Z - N_X = 0.029$  (Gillson  $^{171}$ );  $N_X = 1.765$ ,  $N_Y = 1.77$ ,  $N_Z = 1.790$ ,  $N_Z - N_X = 0.025$ ;  $N_X = 1.730$ ,  $N_Y = ?$ ,  $N_Z = 1.770$ ,  $N_Z - N_X = 0.040$  (Gillson  $^{171}$ ). These samples with lower indices are called *conichalcite*. Color malachite to yellow-green with  $X =$  green,  $Y =$  yellow-green,  $Z =$  blue-green. Found at Bisbee, Arizona.

**Duftite** ( $\text{CuPbOHAsO}_4$ ) is orthorhombic  $^{170}$  dipyramidal with  $a:b:c = 0.822:1:0.647$ . Space group probably  $Pnna$ .  $a$  7.50,  $b$  9.12,  $c$  5.90 Å. U.C. 4. H. = 3. G. = 6.19. Soluble in acid. Decrepitates, turns black, and fuses easily.  $(- )2V =$  large,  $r > v$  distinct.  $N_X = 2.03$ ,  $N_Y = 2.06$ ,  $N_Z = 2.08$ ,  $N_Z - N_X = 0.05$ .

$^{168}$  W. E. Richmond: *Am. Mineral.*, XXV, 441 (1940). H. Strunz: *Zeit. Krist.*, CI, 496 (1939), gives  $a$  6.22,  $b$  9.57,  $c$  7.74 Å. ( $a$  and  $c$  interchanged above.)

$^{169}$  W. E. Richmond: *Am. Mineral.*, XXV, 441 (1940). H. Strunz: *Zeit. Krist.*, CI, 496 (1939). G. Aminoff [*Min. Abst.*, V, 286 (1933)] gives  $N_Y = 1.707$ .

$^{170}$  H. Strunz: *Zeit. Krist.*, CI, 496 (1939). W. E. Richmond: *Am. Mineral.*, XXV, 441 (1940).

$^{171}$  J. L. Gillson: *Am. Mineral.*, XI, 109 (1926).

Again  $N_X = 2.06$ ,  $N_Y = 2.08$ ,  $N_Z = 2.09$ ,  $N_Z - N_X = 0.03$ . Color and streak pale green. Found at Tsumeb, Southwest Africa.

**Austinite** ( $CaZnOHAsO_4$ ) is orthorhombic disphenoidal<sup>172</sup> with  $a:b:c = 0.826:1:0.656$ . Space group  $P2_12_12_1$ ;  $a$  7.43,  $b$  9.00,  $c$  5.90 Å. U.C. 4. Crystals prismatic sphenoidal with good 110 cleavage. Soluble in HCl.  $G = 4.12$ . The optic plane is 001;  $Z = b$ .  $(+ )2V = 47^\circ$ .  $N_X = 1.759$ ,  $N_Y = 1.763$ ,  $N_Z = 1.783$ ,  $N_Z - N_X = 0.024$ . Colorless. Found at Gold Hill, Utah, and also in Bolivia. Zonal intergrowths of austinite and higginsite have been called *barthite*.<sup>172</sup>

**Wagnerite** ( $Mg_2FPO_4$ ) is monoclinic prismatic<sup>173</sup> with  $a:b:c = 0.957:1:0.757$  ( $b$  axis twice former accepted length),  $\beta = 108^\circ 7'$ . Space group  $P2_1/a$ .  $a$  11.93,  $b$  12.47,  $c$  9.44 Å. U.C. 16. Crystals complex with poor 100 and 210 cleavages;

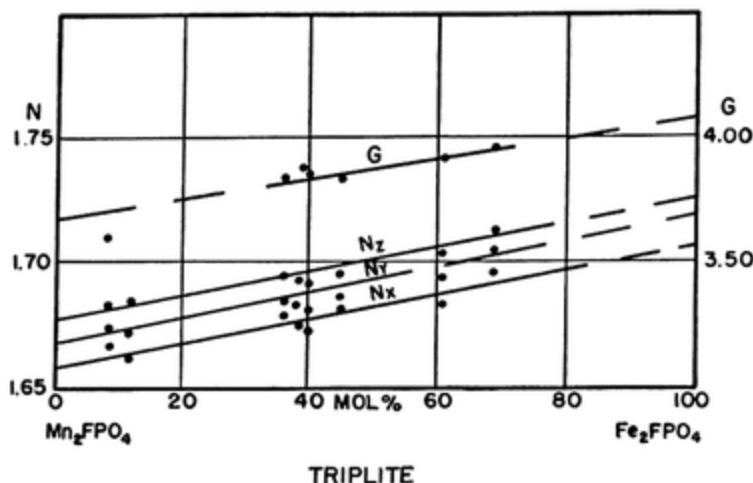


FIG. 120. Properties of triplite.

prismatic cleavage angle  $= 57^\circ 35'$ .  $H = 5$ .  $G = 3$ .  $F = 4$ . Soluble in HCl. The optic plane is 010;  $Z \wedge c = +21.5^\circ$ .  $(+ )2V = 26^\circ$  ca.,  $r > v$ .  $N_X = 1.569$ ,  $N_Y = 1.570$ ,  $N_Z = 1.582$ ,  $N_Z - N_X = 0.013$ . Colorless, yellow, pink, greenish; colorless in section. Found at Werfen, Germany.

**Triplite**<sup>174</sup>  $[(Mn,Fe,Mg,Ca)_2FPO_4]$  is monoclinic prismatic with  $a:b:c = 1.836:1:1.531$ ,  $\beta = 105^\circ 53'$ . Space group  $I2/m(?)$ ;  $a$  11.9,  $b$  6.48,  $c$  9.92 Å. U.C. 8. Perfect 100 and poor 001 cleavages.  $H = 4.5-5$ .  $G = 3.6-3.84$ .  $F = 2.5$ . Soluble in acid.  $(- )2V =$  large (Mn) to  $(+ )2V =$  small (Fe).  $N_X = 1.65-1.69$ ,  $N_Y = 1.66-1.70$ ,  $N_Z = 1.67-1.71$ ,  $N_Z - N_X = 0.014-0.025$ . The optic plane is 010;  $Z \wedge a = 20^\circ - 46^\circ$ . Data follow (see Fig. 120):

MnO	FeO	MgO	CaO	Sign	2V	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$	$Z \wedge a$	$b$	Author
53.77	6.68	0.31	2.17	(-)	$88^\circ$	1.662	1.673	1.684	0.022	$42^\circ$	Y	Hurlbut <sup>122</sup>
34.55	11.68	11.87	2.48	(+)	$28^\circ$	1.651	1.653	1.665	0.014	$22^\circ$	X	Hurlbut <sup>122</sup>
18.40	41.96	0.80	1.69	(+)	Large	1.696	1.704	1.713	0.017	?	?	Otto <sup>175</sup>

<sup>172</sup> L. W. Staples: *Am. Mineral.*, XX, 112 (1935). Also W. Brender: *Am. Mineral.*, XXIII, 347 (1938); W. E. Richmond: *Am. Mineral.*, XXV, 441 (1940). E. Fischer: *Zeit. Krist.*, CV, 268 (1944).

<sup>173</sup> O. Kraus and F. Mussgnug: *Naturw.*, XXVI, 801 (1938). W. E. Richmond: *Am. Mineral.*, XXV, 441 (1940).

<sup>174</sup> C. W. Wolfe and E. W. Heinrich: *Am. Mineral.*, XXXII, 518 (1947). W. E. Richmond: *Am. Mineral.*, XXV, 441 (1940).

<sup>175</sup> H. Otto: *Tsch. Min. Pet. Mit.*, XLVII, 89 (1936).

Color salmon pink or brown with  $X > Z > Y$ . *Sarcopside* is a variety of triplite containing an appreciable tenor of CaO. In it  $Z \wedge c = 45^\circ$ ,  $N_Y = 1.725$ ,  $N_Z - N_X =$  very weak. Color flesh red to lavender, altering to blue-green or brown; streak light yellow; colorless in section. Found in pegmatite and quartz veins, as at Limoges, France.

**Triploidite**<sup>176</sup>  $[(Mn,Fe)_2OHPO_4]$  is monoclinic prismatic with  $a:b:c = 0.928:1:0.746$ ,  $\beta = 108^\circ 14'$ .  $a$  12.26,  $b$  13.38,  $c$  9.90 Å. With  $Fe > Mn$  it has been named wolfeite.<sup>177</sup> Crystals prismatic with good 100 and poor 120 and 010 cleavages.

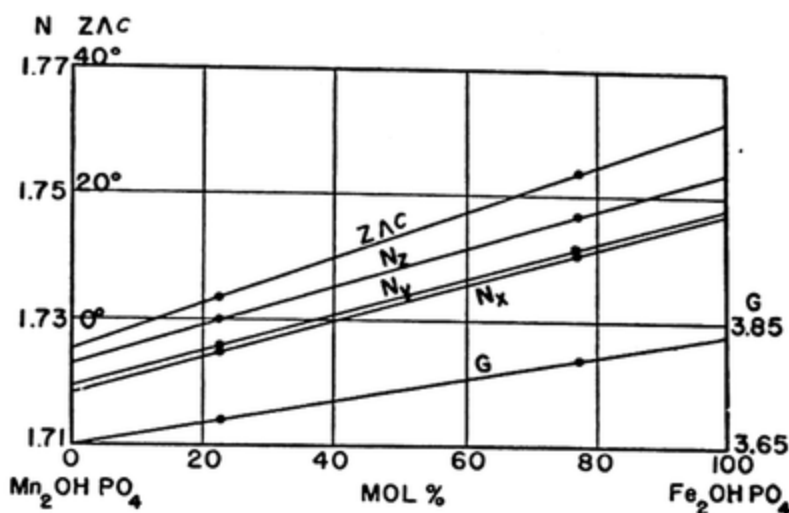


FIG. 120a. Properties of triploidite.

H. = 5.5. G. = 3.78. F. = 1.5. Soluble in acid. The optic plane is 010;  $Z \wedge c = 4^\circ$  to  $31^\circ$ . (+)2V = medium,  $r > v$  strong. Data follow (see Fig. 120a):

MnO	FeO	MgO	Sign	2V	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$	$Z \wedge c$	Author
48.55	14.88		+	Mod.	1.725	1.726	1.730	0.005	$4^\circ$	Fron del <sup>177</sup>
13.12	44.44	2.28	+	Mod.	1.741	1.742	1.746	0.005	$31^\circ$	Fron del <sup>177</sup>

Color yellowish to reddish brown; colorless in section. Found in pegmatite at Branchville, Connecticut; Hagendorf, Bavaria; and Palermo, New Hampshire.

**Sarkinite**<sup>178</sup>  $(Mn_2OHASO_4)$  is monoclinic prismatic with  $a:b:c = 1.874:1:1.504$ ,  $\beta = 108^\circ 58'$ . Space group  $P2_1/a$ ;  $a$  12.7,  $b$  6.78,  $c$  10.2 Å. U.C. 8. Crystals have distinct 100 cleavage. H. = 4–4.5. G. = 4.2. F. = 4. Soluble in HCl. The optic plane is 010;  $Z \wedge c = -36^\circ$  to  $-43^\circ$ . (–)2V =  $83^\circ$ ,  $r > v$  strong.  $N_X = 1.793$ ,  $N_Y = 1.807$ ,  $N_Z = 1.809$ .  $N_Z - N_X = 0.013$  (Larsen<sup>27</sup>);  $N_1 = 1.7930$ ,  $N_2 = 1.8065$ ,  $N_3 = 1.8085$ ,  $N_3 - N_1 = 0.0155$  (Flink<sup>178</sup>); (–)2V = large,  $r < v$ ,  $N_X = 1.790$ ,  $N_Y = 1.794$ ,  $N_Z = 1.798$ ,  $N_Z - N_X = 0.008$  (Palache<sup>179</sup>). Color rose-red. Found at Pajsberg and Långban, Sweden.

**Herderite**  $[CaBe(OH,F)PO_4]$  is monoclinic prismatic<sup>180</sup> with  $a:b:c = 1.276:1:0.625$ ,  $\beta = 90^\circ 6'$ ; space group  $P2_1/c$ ;  $a$  9.80,  $b$  7.68,  $c$  4.80 Å. U.C. 4. Crystals

<sup>176</sup> W. E. Richmond: *Am. Mineral.*, XXV, 441 (1940); P. Kokkoros: *Cent. Mineral.*, 1938A, 278; also G. Hägele: *Cent. Mineral.*, 1938A, 267.

<sup>177</sup> C. Fron del: *Am. Mineral.*, XXXIV, 692 (1949).

<sup>178</sup> G. Flink: *Geol. För. Förh.*, XLVI, 661 (1924).

<sup>179</sup> C. Palache, L. H. Bauer, and H. Berman: *Am. Mineral.*, XXIII, 527 (1938).

<sup>180</sup> W. E. Richmond: *Am. Mineral.*, XXV, 441 (1940). F. Machatschki: *Zeit. Krist.*, CIII, 221 (1941).



short prismatic, with twinning on 100. Poor 110 cleavage.  $H. = 5$ .  $G. = 3.0$ .  $F. =$  difficult. Soluble in acid. The optic plane is 010;  $Z \wedge c = +3.5^\circ$ .  $(- )2V = 74^\circ$ ,  $r > v$ , with distinct inclined extinction.  $N_X = 1.592$ ,  $N_Y = 1.612$ ,  $N_Z = 1.621$ ,  $N_Z - N_X = 0.029$ . Color yellowish to greenish. Found in pegmatite, as at Stoneham, Maine.

**Tilasite**  $[CaMg(F,OH)AsO_4]$  is monoclinic prismatic<sup>180</sup> with  $a:b:c = 0.839:1:0.750$ ,  $\beta = 121^\circ 0'$ . Space group  $C2/c$ ;  $a$  7.56,  $b$  8.95,  $c$  6.66 Å. U.C. 4. Crystals imperfect, with 010 cleavage.  $H. = 5$ .  $G. = 3.77$ . Soluble in acid.  $Z$  normal to 010;  $X \wedge c = +30^\circ$ ;  $X$  nearly normal to  $\bar{1}01$ .  $(- )2V = 82^\circ 14'$ ,  $N_X = 1.640$ ,  $N_Y = 1.660$ ,  $N_Z = 1.675$ ,  $N_Z - N_X = 0.035$ . Color pale green to gray. Found in manganese deposits at Långban, Sweden.

**Durangite**  $(NaAlFAsO_4)$  is monoclinic prismatic<sup>180</sup> with  $a:b:c = 0.856:1:0.772$ ,  $\beta = 119^\circ 22'$ . Space group  $C2/c$ ;  $a$  7.30,  $b$  8.46,  $c$  6.53 Å. U.C. 4. Crystals pyramidal, with 110 cleavages at  $69^\circ 50'$ .  $H. = 5$ .  $G. = 3.94-4.07$ .  $F. = 2$ . Decomposed by  $H_2SO_4$ .  $Z = b$ ;  $X \wedge c = +25^\circ$ ; distinct horizontal dispersion;  $(- )2V = 57^\circ$ ,  $r < v$  weak.  $N_X = 1.634$ ,  $N_Y = 1.673$ ,  $N_Z = 1.685$ ,  $N_Z - N_X = 0.051$ . Color orange-red with  $X =$  orange-yellow,  $Y =$  pale orange-yellow,  $Z =$  nearly colorless. Found in a tin mine in Mexico.

**Augelite**  $[Al_2(OH)_3PO_4]$  is monoclinic prismatic<sup>181</sup> with  $a:b:c = 1.642:1:0.635$ ,  $\beta = 112^\circ 26'$ . Space group  $C2/m$ ;  $a$  13.10,  $b$  7.96,  $c$  5.06 Å. U.C. 4. Crystals tabular or prismatic, with perfect 110 and good  $\bar{2}01$  cleavages.  $H. = 5$ .  $G. = 2.7$ .  $F. = 7$ . Nearly insoluble.  $X = b$ ,  $Z \wedge c = -34^\circ$ .  $(+ )2V = 51^\circ$ ,  $N_X = 1.5736$ ,  $N_Y = 1.5759$ ,  $N_Z = 1.5877$ ,  $N_Z - N_X = 0.0141$ . Colorless. Found in ore deposits, as at Oruro, Bolivia.

**Brazilianite**<sup>182</sup>  $[NaAl_3(OH)_4P_2O_8]$  is monoclinic prismatic with  $a:b:c = 1.106:1:0.699$ ,  $\beta = 97^\circ 22'$ . Space group<sup>183</sup>  $P2_1/n$ ;  $a$  11.19,  $b$  10.08,  $c$  7.06 Å. U.C. 2. Crystals often large equant with many faces; prism zone faces vertically striated. Perfect 010 cleavage.  $H. = 5.5$ .  $G. = 2.98$ .  $F. = 6$ .  $X \wedge c = +20^\circ$ .  $Y = b$ .  $(+ )2V = 70^\circ-75^\circ$ ,  $r < v$ , weak.  $N_X = 1.602$ ,  $N_Y = 1.609$ ,  $N_Z = 1.623$ ,  $N_Z - N_X = 0.021$  (Fron del<sup>184</sup>). Color yellow-green in mass. Found in pegmatite in Minas Gerães, Brazil, and in Grafton County, New Hampshire.

**Dufrenite**  $[Fe''Fe'''_4(OH)_5(PO_4)_3 \cdot 2H_2O?]$  is orthorhombic<sup>185</sup> with  $a:b:c = 0.873:1:0.426$ . Crystals rare; fibrous or lamellar, with perfect 010 and distinct 100 cleavages.  $H. = 3.5-4.5$ .  $G. = 3.2-3.4$ .  $F. = 2.5$ . Soluble in acid. The optic plane is 100,  $Z = b$ . Crystals show zonal growths and wide variations in the optic angle with extreme dispersion.  $(+ )2V =$  very small to moderate; said to exceed  $90^\circ$  (rare).  $r < v$ . Also less commonly  $r > v$ . Examples follow:

$Fe_2O_3$	$FeO$	Sign	2V	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$	Locality
47.03	6.80	+	Sm.	1.810	1.813	1.855	0.045	Cornwall
56.5	2.20	+	Sm.	1.820	1.830	1.925	0.105	Rock Run, Ala.
55.6	?	+	Sm.	1.837	1.845	1.895	0.058	Cornwall
?	?	+	Mod.	1.845	1.855	1.890	0.045	Hirschberg

<sup>181</sup> M. A. Peacock and D. A. Moddle: *Mineral. Mag.*, XXVI, 105 (1941).

<sup>182</sup> F. H. Pough and E. P. Henderson: *Am. Mineral.*, XXX, 572 (1945).

<sup>183</sup> C. S. Hurlbut and E. J. Weichel: *Am. Mineral.*, XXXI, 507 (1946).

<sup>184</sup> C. Fron del and M. L. Lindberg: *Am. Mineral.*, XXXIII, 135 (1948).

<sup>185</sup> C. Fron del: *Am. Mineral.*, XXXIV, 513 (1949). Orthorhombic according to personal communication, Oct. 15, 1949. The "crossed dispersion" is "apparently due to subparallel growth in fibers."

Cleavage pieces show no extinction in white light, but abnormal green, orange, and red interference colors over a wide angle; fibers turned normal to Y show sharp parallel extinction. Color green or, by alteration, yellow or brown. Strongly pleochroic with colors varying, for example:

X	Y	Z	Absorption	Locality
Pale yellow-brown	Pale brown to olive brown	Dark brown or red-brown	$Z > Y > X$	Cornwall
Deep bluish green	Pale yellow brown	Deep olive brown	$Z > Y > X$	Hirschberg
Pale yellow brown	Deep blue	Deep greenish blue	$Z > Y > X$	Cornwall
Deep blue	Buff	Deep red-brown or olive brown	$Z > X > Y$	Rock Run

Found near Siegen, Germany; Wheal Phoenix, Cornwall; Rock Run, Alabama.

**Rockbridgeite-Frondelite**  $[\text{Fe}''\text{Fe}'''_4(\text{OH})_5(\text{PO}_4)_3 \text{ to } \text{Mn}''\text{Fe}'''_4(\text{OH})_5(\text{PO}_4)_3]$  is orthorhombic with  $^{186} a:b:c = 0.816:1:0.308$ . For Fe:  $a$  13.73,  $b$  16.82,  $c$  5.18 Å. and for Mn:  $a$  13.89,  $b$  17.01,  $c$  5.21 Å. Identical in appearance with fibrous dufrenite, but has different X-ray pattern. Excellent 100 and good 010 cleavages.  $H. = 3.5-4.5$ .  $G. = 3.45$ . X or Y parallel with  $c$ ;  $Z = a$ .  $(+)2V = \text{moderate to large}$ . Dispersion  $r < v$ , or (for frondelite)  $r > v$ , extreme in both cases. Cleavage pieces show abnormal interference colors, due to dispersion. Optic data are:

$\text{Fe}_2\text{O}_3$	FeO	MnO	Sign	2V	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$	Locality
50.85	6.14	0.40	+	Mod.	1.873	1.880	1.895	0.022	Rockbridge Co., Va.
55.00	2.66	2.84	+	Mod.	1.838	Varies	1.915	0.077	Polk Co., Ark.
55.84	0.99	2.24	+	Mod.	1.875	1.890	1.920	0.045	Palermo mine
48.85	0.00	7.74	-	Mod.	1.860	1.880	1.893	0.033	Sepucaia, Brazil

Color greenish brown to black or yellow to olive brown. Strongly pleochroic with Z showing maximum absorption. Colors vary; for example:

X	Y	Z	Locality
Pale yellow brown	Bluish green	Dark bluish green	Rockbridge Co., Va.
Pale yellow brown	Yellow-brown to olive brown	Brown to olive brown	Polk Co., Ark.
Pale yellow brown	Orange-brown	Orange-brown	Sepucaia, Brazil

Found in Rockbridge County, Virginia; Polk County, Arkansas; Palermo and Fletcher quarries, New Hampshire; Sepucaia, Brazil.

**Spodiosite** ( $\text{Ca}_2\text{FPO}_4$ ) is triclinic(?) but said <sup>187</sup> to be pseudomorphous after an unknown mineral and structurally identical with apatite. Optically it is quite unlike apatite. It has a prism angle of  $84^\circ$ .  $H. = 5$ .  $G. = 2.94(?)$ . Soluble in acid. Extinction angle <sup>27</sup> on one cleavage (010) is at  $38^\circ$  to the other (001).  $(+)2V = 69^\circ$ ,  $r > v$  rather strong.  $N_X = 1.633$ ,  $N_Y = 1.674$ ,  $N_Z = 1.699$ ,  $N_Z - N_X = 0.036$ . Color ash-gray or brown. Found in Wermland, Sweden.

<sup>186</sup> C. Frondel: *Am. Mineral.*, XXXIV, 513 (1949). Crossed dispersion "apparently derived from subparallel growth in fibers." M. L. Lindberg: *Am. Mineral.*, XXXIV, 541 (1949).

<sup>187</sup> H. Strunz: *Naturw.*, XXVII, 423 (1939).

**Tarbuttite** ( $Zn_2OHPO_4$ ) is triclinic pinacoidal<sup>188</sup> with  $a:b:c = 0.627:1:0.596$ ,  $\alpha = 89^\circ 34'$ ,  $\beta = 91^\circ 37'$ ,  $\gamma = 107^\circ 47'$ . Space group  $\bar{1}$ ;  $a$  8.062,  $b$  12.86,  $c$  7.687 Å. U.C. 8. Crystals complex, with 010 cleavage. H. = 3.5–4. G. = 4.15. F. = easy. Soluble in HCl. X is at  $\phi = 7^\circ$ ,  $\rho = 58^\circ$ ; Y is at  $\phi = 159^\circ$ ,  $\rho = 25^\circ$ ; Z is at  $\phi = -86^\circ$ ,  $\rho = 80^\circ$ .  $(- )2V = 50^\circ$ ,  $N_X = 1.660$ ,  $N_Y = 1.705$ ,  $N_Z = 1.713$ ,  $N_Z - N_X = 0.053$ .  $N_1 - N_2$  on 001 = 0.0145. Again:<sup>189</sup>  $N_X = 1.6625$ ,  $N_Y = 1.7001$ ,  $N_Z = 1.7075$ ,  $N_Z - N_X = 0.045$ ,  $2V = 47^\circ$ . Colorless to brownish. Found in the zinc mines at Broken Hill, Rhodesia.

# **AMBLYGONITE**

TRICLINIC PINACOIDAL<sup>188</sup>

$LiAl(F,OH)PO_4$

$a:b:c = 0.726:1:0.703$      $\alpha = 111^\circ 59'$      $\beta = 97^\circ 46'$      $\gamma = 68^\circ 16'$

**COMP.** There is a continuous series from  $LiAlFPO_4$  to  $LiAlOHPO_4$  (called *montebrasite*); also some Na may proxy for Li. An excess of  $H_2O$  commonly present.

**STRUC.** Space group  $P\bar{1}$ ;  $a$  5.18,  $b$  7.11,  $c$  5.03 Å. U.C. 2.

**PHYS. CHAR.** Crystals tabular to equant. Multiple lamellar twinning on  $\bar{1}\bar{1}1$  common; also on 111, uncommon. Perfect 100, good 110, and distinct  $0\bar{1}1$  cleavages. H. = 6. G. = 3–3.1. F. = 2. Soluble in  $H_2SO_4$ .

**OPT. PROP.** In a sample<sup>190</sup> with only 4.6 mol. %  $LiAlOHPO_4$  the optic plane makes an angle of  $12^\circ$  with  $0\bar{1}1$  and  $76^\circ$  with 110 in the acute angle between  $0\bar{1}1$  and 110; X lies in  $0\bar{1}1$  and makes an angle of  $17^\circ$  with the edge 110: $0\bar{1}1$ . For the same sample:  $(- )2V = 50^\circ$  ca.,  $r > v$ , with strong crossed and distinct inclined dispersion. A sample with about 10%  $LiAlOHPO_4$  has  $N_X = 1.578$ ,  $N_Y = 1.593$ ,  $N_Z = 1.598$ ,  $N_Z - N_X = 0.020$ . Color greenish, violet, pink, white. With increase in the tenor of  $LiAlOHPO_4$  the optic angle about X increases, the density decreases, the refringence increases considerably, and the birefringence increases slowly, as shown approximately in Fig. 121. With<sup>191</sup> about 65%  $LiOHPO_4$  the optic angle is  $55^\circ$  and the orientation is: for X,  $\phi = 19^\circ 30'$ ,  $\rho = 83^\circ$ ; for Y,  $\phi = -72^\circ 30'$ ,  $\rho = 69^\circ$ ; for Z,  $\phi = 130^\circ$ ,  $\rho = 21^\circ$ . With about 85 mol. %  $LiAlOHPO_4$ :  $(+ )2V = 80^\circ \pm$ ,  $r < v$ , with horizontal and weak inclined dispersion.  $N_X = 1.607$ ,  $N_Y = 1.614$ ,  $N_Z = 1.630$ ,  $N_Z - N_X = 0.023$ . Color white.

**OCCUR.** Found in pegmatite, often associated with tourmaline and lithium minerals, as at Hebron, Maine.

**Fremontite** [ $NaAl(OH,F)PO_4$ ] is triclinic and much like amblygonite.<sup>192</sup> It shows two directions of lamellar twinning. G. = 3.09. Perfect 001, good 100, and one other cleavage. X nearly normal to 001; in a cleavage piece  $Z' \wedge$  twinning =  $29^\circ$ .  $(+ )2V$  = very large,  $N_X = 1.594$ ,  $N_Y = 1.603$ ,  $N_Z = 1.615$ ,  $N_Z - N_X = 0.021$ . Again:<sup>193</sup>  $(- )2V$  = large,  $N_X = 1.586$ ,  $N_Y = ?$ ,  $N_Z = 1.607$ . Also:  $2V$  near  $90^\circ$ ,  $N_Y = 1.618$ . Color gray to white; also green. Found in pegmatite as at Canon City, Colorado.

<sup>188</sup> S. Tengner: *Geol. För. Förh.*, LXII, 332 (1941); W. E. Richmond: *Am. Mineral.*, XXV, 441 (1940); C. Palache, W. E. Richmond, and C. W. Wolfe: *Am. Mineral.*, XXVIII, 39 (1943).

<sup>189</sup> H. Buttgenbach and J. Mélon: *Min. Abst.*, V, 137 (1932).

<sup>190</sup> H. Backlund: *Geol. För. Förh.*, XL, 757 (1918).

<sup>191</sup> W. E. Richmond and C. W. Wolfe: *Am. Mineral.*, XXVIII, 39 (1943).

<sup>192</sup> H. Strunz: *Cent. Mineral.*, 1939A, 248.

<sup>193</sup> J. Sekanina: *Fortschr. Mineral.*, XXI, 388 (1937).

**Chenevixite**  $[\text{CuFe}(\text{OH})_2\text{AsO}_4]$  is cryptocrystalline.  $H. = 4$ .  $G. = 3.9$ .  $F. = 2.5$ . Optic sign unknown.  $N = 1.88$  ca.  $N_z - N_x =$  rather strong. Color green to greenish yellow. Found in copper ores in the Tintic district, Utah.

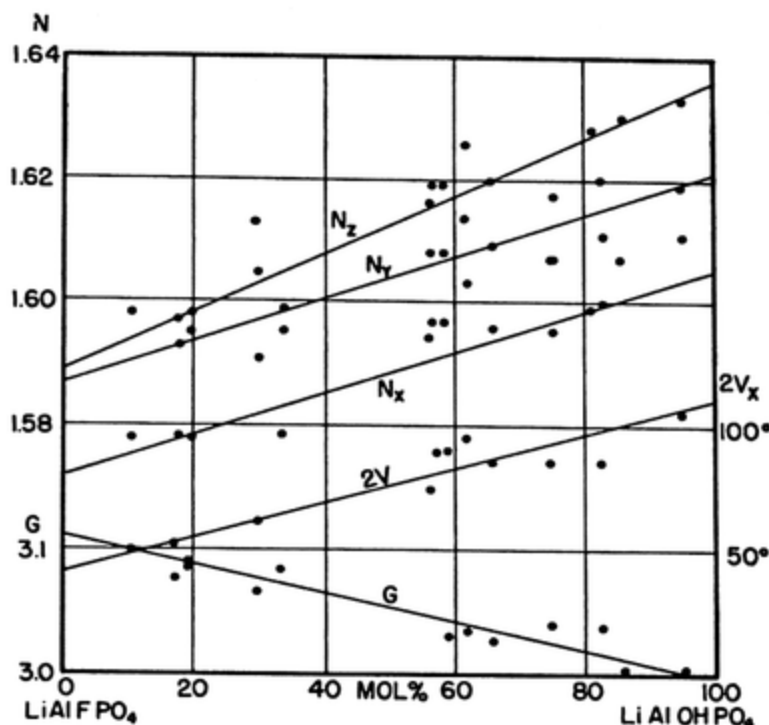


FIG. 121. Properties of amblygonite.

## (b) WITH ADDITIONAL ANIONS—HYDROUS

**Arseniosiderite**<sup>17</sup>  $[\text{Ca}_3\text{Fe}_4(\text{OH})_6(\text{AsO}_4)_4 \cdot 3\text{H}_2\text{O}]$  is tetragonal, with basal cleavage.  $H. = 4.5$ .  $G. = 3.5\text{--}3.9$ .  $F. = 3$ . Soluble in acid. Uniaxial negative with  $N_O = 1.870$ ,  $N_E = 1.792$ ,  $N_O - N_E = 0.078$ . *Mazapilite* is probably arseniosiderite pseudomorphous after scorodite.<sup>194</sup> It has  $N_O = 1.898$ ,  $N_E = 1.815$ ,  $N_O - N_E = 0.083$ . Color yellow or brown with O = reddish brown, E = nearly colorless or clear yellow. Found in ore deposits, as at Romanèche, France.

**Wardite**<sup>195</sup>  $[\text{Na}_4\text{CaAl}_{12}(\text{OH})_{18}(\text{PO}_4)_8 \cdot 6\text{H}_2\text{O}]$  is tetragonal pyramidal(?) with  $c/a = 2.68$ . Space group  $P4_1$ ,  $P4_2$ , or  $P4_3$ ;  $a$  7.04,  $c$  18.88 Å. U.C. 1. Crystals pyramidal with perfect basal cleavage.  $H. = 4.5\text{--}5$ .  $G. = 2.81$ .  $F. = 3$ . Uniaxial positive with  $N_O = 1.590$ ,  $N_E = 1.599$ ,  $N_E - N_O = 0.009$ . Basal sections may show four biaxial segments with  $(+)2V =$  small. Found at Cedar Valley, Utah.

**Millisite**<sup>196</sup>  $[\text{Na}_2\text{Ca}_2\text{Al}_{12}(\text{OH})_{18}(\text{PO}_4)_8 \cdot 6\text{H}_2\text{O}]$  is tetragonal(?) much like wardite.  $H. = 5.5$ .  $G. = 2.83$ .  $F. = 3.5$ . Fibers have negative elongation.  $(+)2V =$  moderate,  $N_x = 1.584$ ,  $N_y = 1.598$ ,  $N_z = 1.602$ ,  $N_z - N_x = 0.018$ . Also reported<sup>196</sup> to have indices slightly lower than those of wardite. Color white. Found at Fairfield, Utah.

<sup>194</sup> E. S. Larsen: *Am. Mineral.*, III, 12 (1918).

<sup>195</sup> E. S. Larsen, 3d: *Am. Mineral.*, XXVII, 281 (1942). F. H. Pough: *Min. Abst.*, VII, 165 (1938). *Soumansite* is a synonym of wardite—*Am. Mineral.*, XV, 307 (1930).

**Dussertite** <sup>196</sup>  $[BaFe_3(OH)_5(AsO_4)_2 \cdot H_2O]$  is hexagonal and related to jarosite. Basal plates.  $H. = 3.5$ .  $G. = 3.75$ . Soluble in dilute HCl. Uniaxial negative with  $N_O = 1.87$ ,  $N_E = 1.85$ ,  $N_O - N_E = 0.02$ . Also <sup>196</sup>  $(- )2V = 15-20^\circ$ ,  $N_O = 1.870$ ,  $N_E = 1.845$ . Yellowish green in section with  $O > E$  weak. Found in sediments in Algeria and at Mapimi, Mexico.

**Dennisonite** <sup>197</sup>  $[Ca_3Al(OH)_3(PO_4)_2 \cdot H_2O]$  is hexagonal with perfect basal cleavage.  $H. = 4.5$ .  $G. = 2.85$ . Uniaxial negative with <sup>197</sup>  $N_O = 1.601$ ,  $N_E = 1.591$ ,  $N_O - N_E = 0.010$ . Again: <sup>198</sup>  $N_O = 1.633$ ,  $N_E = 1.628$ ,  $N_O - N_E = 0.005$ . Fibers have negative elongation and parallel extinction. Color white. Found in nodules near Fairfield, Utah.

**Pseudowavellite** <sup>196</sup>  $[CaAl_3(OH)_5(PO_4)_2 \cdot H_2O]$  forms a (probably) continuous isomorphous series <sup>199</sup> with *deltaite*  $[Ca_2Al_2(OH)_4(PO_4)_2 \cdot H_2O]$ . It may contain some  $Fe_2O_3$ ; also BaO. Dennisonite chemically seems to belong to the same series, but optically is unrelated. Pseudowavellite is ditrigonal pyramidal with  $c/a = 2.307$ .  $a$  6.98,  $c$  16.10 Å. Space group  $R3m$ . U.C. 1. Crystals often prismatic, with perfect basal cleavage.  $H. = 5$ .  $G. = 2.92-2.95$ .  $F. = 2.5$ . Uniaxial positive with  $N_O = 1.59-1.645$ ,  $N_E = 1.60-1.655$ ,  $N_E - N_O = 0.01$  ca. Deltaite has the higher refractive indices. Found in nodules near Fairfield, Utah.

**Cacoxenite**  $[Fe_2(OH)_3PO_4 \cdot 4.5H_2O]$  is hexagonal (Larsen <sup>27</sup>) or orthorhombic (Lacroix <sup>28</sup>). Fibrous.  $H. = 3-4$ .  $G. = 3.38$ .  $F. = 2.5-3$ . Soluble in HCl. Uniaxial positive with  $N_O = 1.580-1.585$ ,  $N_E = 1.640-1.656$ ,  $N_E - N_O = 0.060-0.071$  (Larsen <sup>27</sup>). Color yellow, becoming darker when exposed to air. Distinctly pleochroic with  $O =$  pale yellowish,  $E =$  orange to canary yellow, and  $O < E$ . Found in ore deposits, as at the Hrbek mine, Bohemia.

**Dewindtite**  $[Pb_3(UO_2)_5(OH)_4(PO_4)_4 \cdot 10H_2O]$  is orthorhombic; crystals minute {100} plates with 100 cleavage.  $G. = 4.08$ . Soluble in  $HNO_3$ . The optic plane is 001;  $X = a$ .  $(+)2V =$  large,  $r < v$ .  $N_X = 1.762$  ca.,  $N_Y = 1.763$  ca.,  $N_Z = ?$ , but  $N_Y - N_X = 0.004$  ca. Color canary yellow, not pleochroic. Found with torbernite in the Congo.

**Sampleite** <sup>200</sup>  $[NaCaCu_5Cl(PO_4)_4 \cdot 5H_2O]$  is orthorhombic dipyramidal with  $a:b:c = 0.253:1:0.251$ . Space group  $Pmmm$ ;  $a$  9.70,  $b$  38.40,  $c$  9.65 Å. U.C. 8. Crystals {010} plates with perfect 010 and good 100 and 001 cleavages.  $H. = 5$ .  $G. = 3.20$ .  $F. = 2$ . The optic plane is 100;  $X = b$ .  $(-)2V = 5^\circ-20^\circ$ ,  $r > v$ .  $N_X = 1.629$ ,  $N_Y = 1.677$ ,  $N_Z = 1.679$ ,  $N_Z - N_X = 0.050$ . Blue to bluish green with  $X =$  deep blue,  $Y =$  light blue,  $Z =$  colorless. Found in sericitized rock at Chuquicamata, Chile.

**Fischerite**  $[Al_2(OH)_3PO_4 \cdot 2.5H_2O]$  is orthorhombic with  $a:b:c = 0.594:1:?$  Crystals small prisms.  $H. = 5$ .  $G. = 2.46$ .  $X = b$ ,  $Y = a$ .  $(+)2V =$  large,  $N = 1.57-1.58$ . Color green. Found in veins in the Urals; also in Hungary.

**Mixite**  $[Cu_{10}Bi(OH)_8(AsO_4)_5 \cdot 7H_2O?]$  is orthorhombic in acicular crystals.  $H. = 3-4$ .  $G. = 3.79$ .  $F. = 2$ . Coated white in  $HNO_3$ .  $Z = c$ .  $(+)2V = 0^\circ$  to very small;  $N_X = 1.745$  (1.730),  $N_Y = 1.745$ ,  $N_Z = 1.830$  (1.810),  $N_Z - N_X = 0.085$ . Color emerald green, in thin section pale green, not pleochroic. Found in copper-ore deposits in the Tintic district, Utah.

<sup>196</sup> D. McConnell: *Am. Jour. Sci.*, CCXL, 649 (1942). W. F. Foshag: *Am. Mineral.*, XXII, 479 (1937).

<sup>197</sup> E. S. Larsen and E. V. Shannon: *Am. Mineral.*, XV, 307 (1930).

<sup>198</sup> D. Guimarães: *Min. Abst.*, VI, 8 (1935).

<sup>199</sup> E. S. Larsen, 3d: *Am. Mineral.*, XXVII, 281, 350, and 441 (1942).

<sup>200</sup> C. S. Hurlbut: *Am. Mineral.*, XXVII, 586 (1942).



**Leucochalcite** ( $\text{Cu}_2\text{OHAsO}_4 \cdot \text{H}_2\text{O}$ ) is orthorhombic and acicular parallel to  $c$ .  $F. = 2-2.5$  to a black glass.  $Y = c$  (Larsen <sup>27</sup>);  $Z = c$  (Lacroix <sup>25</sup>).  $(+ )2V = \text{large}$ ,  $r < v$  strong.  $N_X = 1.79$ ,  $N_Y = 1.807$ ,  $N_Z = 1.84$ ,  $N_Z - N_X = 0.05$ . Color white; silky. Found in the oxide zone of some copper deposits at Spessart, Germany.

**Euchroite** [ $\text{Cu}_2\text{OHAsO}_4 \cdot 3\text{H}_2\text{O}$ ] is orthorhombic disphenoidal <sup>261</sup> with  $a:b:c = 0.957:1:0.582$ . Space group  $P2_12_12_1$ ;  $a$  10.05,  $b$  10.50,  $c$  6.11 Å. U.C. 4. Crystals domatic with striations parallel to  $b$  and difficult 101 and 010 cleavages.  $H. = 3.5-4$ .  $G. = 3.41$ .  $F. = 2-2.5$ . Soluble in  $\text{HNO}_3$ . The optic plane is 001;  $Z = b$ .  $(+ )2V = 31^\circ$ ,  $r > v$  moderate.  $N_X = 1.695$ ,  $N_Y = 1.698$ ,  $N_Z = 1.733$ ,  $N_Z - N_X = 0.038$ . Color emerald to leek green. In section bright bluish green, faintly or non-pleochroic. Found in slate at Libethen, Hungary.

**Childrenite** [ $\text{Fe}''\text{Al}(\text{OH})_2\text{PO}_4 \cdot \text{H}_2\text{O}$ ] forms a (probably) continuous series with *eosphorite* [ $\text{Mn}''\text{Al}(\text{OH})_2\text{PO}_4 \cdot \text{H}_2\text{O}$ ]. Elements also present in small amount include  $\text{Fe}'''$ ,  $\text{Mg}$ ,  $\text{Be}$ ,  $\text{Ca}$ ,  $\text{F}$ . Childrenite is orthorhombic pyramidal <sup>262</sup> with  $a:b:c = 0.776:1:0.517$ . Space group  $Pba$ ;  $a$  10.35,  $b$  13.34,  $c$  6.90 kX. U.C. 8. Crystals pyramidal or prismatic, vertically striated, with 100 cleavage.  $H. = 4.5-5$ .  $G. = 3.1-3.25$ .  $F. = 4$ . Soluble in  $\text{HCl}$ . The optic plane is 100;  $X = b$ .  $(- )2V = 40-45^\circ$ ,  $r > v$  strong ( $r < v$  in *eosphorite*).  $N_X = 1.63-1.645$ ,  $N_Y = 1.65-1.68$ ,  $N_Z = 1.66-1.685$ ,  $N_Z - N_X = 0.03-0.04$ . Color white, rose-pink, yellow, bluish, brown with  $X = \text{colorless}$  or yellowish,  $Y = \text{yellowish}$  or deep pink,  $Z = \text{brown}$  or nearly colorless. Found in pegmatites, as at Hebron, Maine.

**Carnotite** [ $\text{K}_2(\text{UO}_2)_2(\text{OH})_2(\text{VO}_4)_2 \cdot 3\text{H}_2\text{O}$ ] is orthorhombic in basal plates with angles of  $78^\circ$  and  $102^\circ$ . Perfect 001 cleavage. Soft.  $X = c$ ;  $Y = a$ .  $(- )2V = 39-50^\circ$ ,  $r < v$  weak. Indices rise with decrease in tenor of  $\text{H}_2\text{O}$ .

$\text{H}_2\text{O}$	$2V$	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$	Authority
4.57(?)	?	?	1.895	1.92	?	Larsen <sup>27</sup>
?	$43^\circ$	1.750	1.925	1.95	0.200	Larsen <sup>27</sup>
1.72	?	?	2.04	2.06	?	Hess <sup>203</sup>
1.32	$50^\circ$	?	2.06	2.08	?	Hess <sup>203</sup>

Color yellow. Colorless in section or light colored with  $X = \text{grayish yellow}$ ,  $Y$  and  $Z = \text{lemon yellow}$ . Found in sandstone in Montrose County, Colorado.

**Ludlamite** [ $\text{Fe}_6(\text{PO}_4)_4 \cdot 8\text{H}_2\text{O}$ ] is monoclinic prismatic <sup>264</sup> with  $a:b:c = 2.26:1:1.98$ ,  $\beta = 100^\circ 36'$ . Space group  $P2_1/a$ ;  $a$  10.48,  $b$  4.63,  $c$  9.16 Å. U.C. 1. Crystals basal tablets with perfect 001 and distinct 100 cleavages.  $H. = 3-4$ .  $G. = 3.72$ .  $F. = 2-2.5$ . Soluble in  $\text{HCl}$ . The optic plane is 010;  $Z \wedge c = +67^\circ$ .  $(+ )2V = 82^\circ$ ,  $r > v$  weak.  $N_X = 1.653$ ,  $N_Y = 1.675$ ,  $N_Z = 1.697$ ,  $N_Z - N_X = 0.044$  (Larsen <sup>27</sup>);  $N_X = 1.650$ ,  $N_Y = 1.669$ ,  $N_Z = 1.689$ ,  $N_Z - N_X = 0.039$  (Berman <sup>205</sup>). Color bright green. Found in ore deposits at the Wheal Jane mine, Cornwall.

**Englishite** [ $\text{K}_2\text{Ca}_4\text{Al}_8(\text{OH})_{10}(\text{PO}_4)_8 \cdot 9\text{H}_2\text{O}$ ] is monoclinic <sup>199(?)</sup> with perfect basal cleavage.  $H. = 3$ .  $G. = 2.65$ . The optic plane and  $Z$  are normal to 010;  $X$  near  $c$ ;  $Y$  near  $a$ .  $(- )2V = \text{small}$ ,  $N_X = 1.570$ ,  $N_Y = ?$ ,  $N_Z = 1.572$ ,  $N_Z - N_X = 0.002$ . Colorless and glassy clear. Found in nodules at Fairfield, Utah.

<sup>201</sup> L. G. Berry and H. R. Steacy: *Geol. Soc. Am. Bull.*, LVII, 1178 (1946).

<sup>202</sup> W. H. Barnes: *Am. Mineral.*, XXXII, 684 (1947).

<sup>203</sup> F. L. Hess and W. F. Foshag: *Proc. U. S. Nat. Mus.*, LXXII, Art. 12 (1927).

<sup>204</sup> C. W. Wolfe: *Am. Mineral.*, XXXIV, 94 (1949).

<sup>205</sup> H. Berman: *Am. Mineral.*, X, 428 (1925).



**Tagilite** ( $Cu_2OHPO_4 \cdot H_2O$ ) is monoclinic in fibrous concretions with distinct 010 cleavage.  $H. = 3-4$ .  $G. = 4.1$ .  $F. = 2-2.5$ . Soluble in acid. Elongation negative; extinction angle small.  $(- )2V = \text{small}$ .  $N_X = 1.69$ ,  $N_Y = 1.84$ ,  $N_Z = 1.85$ ,  $N_Z - N_X = 0.16$ . Color green. Found on limonite in the Urals.

**Spencerite** [ $Zn_4(OH)_2(PO_4)_2 \cdot 3H_2O$ ] is monoclinic, with excellent 100, perfect 010, and imperfect 001 cleavages nearly at right angles. Lamellar twinning on 100. Crystals {100} tablets.  $H. = 3$ .  $G. = 3.14$ .  $F. = \text{easy}$ . Soluble in acid. The optic plane is normal to 010;  $X \wedge c = 85^\circ \text{ ca.}$  Extinction in 010 at  $6^\circ$  from twinning lines.  $(- )2V = 49^\circ$ ,  $r > v$  moderate.  $N_X = 1.586$ ,  $N_Y = 1.600$ ,  $N_Z = 1.602$ ,  $N_Z - N_X = 0.016$  (Larsen<sup>27</sup>);  $N_X = 1.586$ ,  $N_Y = 1.602$ ,  $N_Z = 1.606$ ,  $N_Z - N_X = 0.020$  (Walker and Parsons<sup>206</sup>). Colorless. Found in a zinc-ore deposit near Salmo, British Columbia, with hemimorphite.

**Isoclasite** ( $Ca_2OHPO_4 \cdot 2H_2O$ ) is monoclinic in vertical needles with perfect 010 cleavage.  $H. = 1.5$ .  $G. = 2.9$ . Soluble in HCl. The optic plane is 010;  $Z \wedge c = \text{small}$ .  $(+ )2V = 50^\circ \text{ ca.}$   $N_X = 1.565$ ,  $N_Y = 1.568$ ,  $N_Z = 1.580$ ,  $N_Z - N_X = 0.015$ . Color white. Found with siderite at Joachimsthal, Bohemia.

**Morinite** [ $HNa_2Ca_3Al_3F_6(PO_4)_4 \cdot 8H_2O$ ] is monoclinic in lamellar masses. Poor 100 cleavage.  $H. = 4$ .  $G. = 2.94$ .  $F. = \text{easy}$ . The optic plane is 010;  $X \wedge c = -30^\circ$ .  $(- )2E = 40^\circ$ ,  $N = 1.555 \text{ ca.}$   $N_Z - N_X = \text{about } 0.01$ . Color wine- to flesh-red. An alteration product of amblygonite found in a tin deposit at Montibras, France.

**Lueneburgite** ( $H_6B_2O_6 \cdot Mg_3P_2O_8 \cdot 5H_2O$ ) is monoclinic. Crystals six-sided basal tablets elongated along  $a$ . Distinct 110 cleavages at  $73^\circ$ .  $G. = 2.05$ . Fusible. Soluble in acid. The optic plane is 010(?); extinction ( $X$  and  $Z$ ) at nearly  $45^\circ$  to elongation.  $(- )2V = \text{medium}$ .  $N_X = 1.521$ ,  $N_Y = 1.541$ ,  $N_Z = 1.547$ ,  $N_Z - N_X = 0.026$ . Colorless. Found in marl of Lueneburg, Germany.

**Bayldonite** [ $(Pb,Cu)_4(OH)_2(AsO_4)_2 \cdot H_2O$ ] is monoclinic(?) and fibrous parallel to  $c$ .  $H. = 4.5$ .  $G. = 4.35$ . Fuses to black bead. Soluble in  $HNO_3$ . The optic plane is normal to 010;  $Z \wedge c = 45^\circ \text{ ca.}$   $(+ )2V = \text{large}$ ,  $r < v$  strong(?).  $N_X = 1.95$ ,  $N_Y = 1.97$ ,  $N_Z = 1.99$ ,  $N_Z - N_X = 0.04$ . Color grass green. Found in Cornwall.

**Lehiite**<sup>197</sup> [ $Na_2Ca_5Al_8(OH)_{12}(PO_4)_8 \cdot 6H_2O$ ] is fibrous and probably monoclinic.  $H. = 5.5$ .  $G. = 2.89$ . Fibers have large extinction angle.  $(- )2V = \text{large}$ .  $N_X = 1.600$ ,  $N_Y = 1.615$ ,  $N_Z = 1.629$ ,  $N_Z - N_X = 0.029$ . Color white. Found in nodules at Fairfield, Utah.

**Chalcosiderite** [ $CuFe''_6(OH)_8(PO_4)_4 \cdot 4H_2O$ ] is triclinic pinacoidal with  $a:b:c = 0.791:1:0.605$ ,  $\alpha = 92^\circ 58'$ ,  $\beta = 93^\circ 30'$ ,  $\gamma = 107^\circ 49'$ . In a different orientation<sup>207</sup>  $a$  7.66,  $b$  10.18,  $c$  7.88 Å. U.C. 1; then  $a:b:c = 0.753:1:0.774$ ,  $\alpha = 112^\circ 29'$ ,  $\beta = 115^\circ 18'$ ,  $\gamma = 69^\circ 00'$ . Crystals in sheaflike aggregates with good 010 cleavage.  $H. = 4.5$ .  $G. = 3.2$ .  $F. = 4-4.5$ . Soluble in HCl. The acute bisectrix  $X$  nearly  $= b$ ; very strong crossed dispersion.  $(- )2V = 24^\circ$ ,  $r > v$  very strong.  $N_X = 1.773$ ,  $N_Y = 1.840$ ,  $N_Z = 1.845$ ,  $N_Z - N_X = 0.072$ . Color siskin-green with  $X = \text{colorless}$ ,  $Y = ?$ ,  $Z = \text{pale green}$  in thick sections. Plates parallel to 010 give no extinction in white light, but very abnormal red, blue, and green interference colors, changing on rotation. Found in copper-ore deposits in Cornwall.

**Turquoise** [ $CuAl_6(OH)_8(PO_4)_4 \cdot 5H_2O$ ] is triclinic pinacoidal with  $a:b:c = 0.752:1:0.772$ ,  $\alpha = 111^\circ 39'$ ,  $\beta = 115^\circ 23'$ ,  $\gamma = 69^\circ 26'$ . Unit cell:  $a$  7.47,  $b$  9.93,  $c$  7.67 Å. U.C. 1. Isomorphous with chalcosiderite. Crystals prismatic, very rare; with dis-

<sup>206</sup> T. L. Walker and A. L. Parsons: *Univ. Toronto Geol. Stud.*, No. 12, 58 (1921).

<sup>207</sup> A. R. Graham and L. G. Berry: *Bull. Geol. Soc. Am.*, LVII, 1198 (1946).

tinct  $1\bar{1}0$  and one other cleavage.  $H. = 5$ .  $G. = 2.84$ .  $F. = 7$ , but turns brown. Soluble in acid only after ignition. Extinction on  $1\bar{1}0$  is at  $12^\circ$  to  $c$  and  $12^\circ$  to  $(0\bar{1}1?)$ . Extinction on the other cleavage is at  $5^\circ$  and  $34^\circ$ .  $(+ )2V = 40^\circ$ ,  $r < v$  strong.  $N_X = 1.61$ ,  $N_Y = 1.62$ ,  $N_Z = 1.65$ ,  $N_Z - N_X = 0.04$ . Color sky blue to bluish green grading to colorless; if colored, it is pleochroic from colorless to pale bluish. Found in veins in trachyte in Persia; in copper ore deposits, as in Chile.

**Delvauxite**<sup>29</sup>  $[\text{Fe}^{'''}_4(\text{OH})_6(\text{PO}_4)_2 \cdot 17\text{H}_2\text{O}]$  is apparently amorphous.  $H. = 2.5$ .  $G. = 1.82\text{--}2.0$ . Isotropic with  $N = 1.72 \pm$ . Color chestnut brown. Found in concretions near Visé, Belgium.

#### 4. Phosphates with type formula $\approx \text{A}_5\text{B}_2\text{X}_8$

##### (a) WITHOUT ADDITIONAL ANIONS

**Metarossite**<sup>208</sup>  $(\text{H}_4\text{CaV}_2\text{O}_8)$  is biaxial with large optic angle. Soft. An optic axis nearly normal to the cleavage.  $N_X = 1.840$ ,  $N_Y > 1.85$ ,  $N_Z = ?$ ,  $N_Z - N_X =$  strong. Strong dispersion. Color yellow. A dehydration product of rossite. Found in San Miguel County, Colorado.

**Rossite**<sup>208</sup>  $(\text{H}_4\text{CaV}_2\text{O}_8 \cdot 2\text{H}_2\text{O})$  is triclinic with  $\alpha = 98^\circ 18'$ ,  $\beta = 97^\circ 24'$ ,  $\gamma = 89^\circ 34'$ . Crystals prismatic with distinct 010 cleavage.  $H. = 2\text{--}3$ .  $G. = 2.45$ .  $Z = c$ ; extinction on 001 at  $16^\circ$  to 010.  $(+ )2V =$  large.  $N_X = 1.710$ ,  $N_Y = 1.770$ ,  $N_Z = 1.840$ ,  $N_Z - N_X = 0.130$ . Strong dispersion. Color yellow. Found in a vein in sandstone in San Miguel County, Colorado.

##### (b) WITH ADDITIONAL ANIONS—ANHYDROUS

**Merrillite**<sup>209</sup>  $(\text{Na}_2\text{Ca}_3\text{OP}_2\text{O}_8)$  is hexagonal with prismatic cleavage.  $G. = 3.10$ . Soluble in  $\text{HNO}_3$ . Uniaxial negative with  $N_O = 1.623$ ,  $N_E = 1.620$ ,  $N_O - N_E = 0.003$ . Extinction often undulatory. Colorless. Found only in meteorites.

**Hamlinite** or *goyazite*  $[\text{H}_2\text{Sr}_2\{\text{Al}(\text{OH})_2\}_6(\text{PO}_4)_4]$  is ditrigonal pyramidal<sup>210</sup> with  $c/a = 1.135$ . Space group  $R3m$ ;  $a$  6.82 Å.,  $\alpha = 61^\circ 28'$ . Granular or tabular with perfect basal cleavage.  $H. = 5$ .  $G. = 3.2$ .  $F. = 4$ . Insoluble in acids. Uniaxial positive with  $N_O = 1.6294$ ,  $N_E = 1.6387$ ,  $N_E - N_O = 0.0093$  (Brazil—Ježek<sup>211</sup>);  $N_O = 1.620$ ,  $N_E = 1.630$ ,  $N_E - N_O = 0.010$  (Colorado—Larsen<sup>27</sup>);  $N_O = 1.634\text{--}1.636$ ,  $N_E = 1.640\text{--}1.642$  (Pitkovskaya<sup>212</sup>). Also biaxial with  $2E = 50^\circ$  (maximum) in hexagonal segments, the optic plane being (nearly) normal to the hexagonal prism face in each segment.  $Y \wedge$  horizontal edge  $= 0^\circ\text{--}5^\circ$ . Some crystals show zonal growths. Colorless to reddish brown with  $O =$  reddish brown, and  $E =$  yellow in thick plates. Again<sup>212</sup>  $O =$  pale pink,  $E =$  pale yellowish or greenish. Found in pegmatite at Stoneham, Maine.

**Gorceixite**<sup>213</sup>  $[\text{H}_2\text{Ba}\{\text{Al}(\text{OH})_2\}_6(\text{PO}_4)_4?]$  is microcrystalline in pebbles.  $H. = 6$ .  $G. = 3.1$ . Uniaxial positive with  $N_O = 1.6253$ ,  $N_E - N_O =$  weak. Color brown or white. Found in diamond sands of Brazil.

<sup>208</sup> W. F. Foshag and F. L. Hess: *Proc. U. S. Nat. Mus.*, LXXII, Art. 11 (1927).

<sup>209</sup> E. V. Shannon and E. S. Larsen: *Am. Jour. Sci.*, CCIX, 250 (1925).

<sup>210</sup> B. Gossner: *Zeit. Krist.*, XCVI, 488 (1937). S. B. Hendricks: *Am. Mineral.*, XXII, 773 (1937).

<sup>211</sup> B. Ježek: *Bull. Int. Acad. Sci. Bohème*, XIII, No. 2 (1908).

<sup>212</sup> Z. N. Pitkovskaya: *Min. Abst.*, VII, 558 (1940). Identification may be uncertain.

<sup>213</sup> A new analysis shows the presence of some Ce,  $\text{Fe}^{'''}$ , Mg. See A. M. Macgregor: *Min. Abst.*, VIII, 274 (1942).

**Plumbogummite**  $[H_2Pb\{Al(OH)_2\}_6(PO_4)_4]$  is gumlike.  $H. = 4-5$ .  $G. = 4.0-4.9$ .  $F. = 2(?)$ . Soluble in  $HNO_3$ . Uniaxial positive with  $N_O = 1.653$ ,  $N_E = 1.675$ ,  $N_E - N_O = 0.022$ . Indices vary about  $\pm 0.01$ . Color yellow or brown; weakly pleochroic in yellow with  $X < Z$ . Found in slate with galena, etc., at Huelgoet, Brittany.

**Arsenoclasite**  $[Mn_5(OH)_4As_2O_8]$  is orthorhombic with  $a:b:c = 0.510:1:0.313$ . Probable space group  $^{214} Pnmm$ ;  $a$  9.19,  $b$  18.01,  $c$  5.79 Å. U.C. 4. Distinct 010 cleavage.  $H. = 5-6$ .  $G. = 4.16$ . The optic plane is 100;  $X = b$ .  $(- )2V = 53^\circ 26'$ .  $N_X = 1.787$ ,  $N_Y = 1.810$ ,  $N_Z = 1.816$ ,  $N_Z - N_X = 0.029$ . Color red. Resembles sarkinite. Found in fissures in dolomite with hausmannite at Långban, Sweden.

**Erinite**  $[Cu_5(OH)_4As_2O_8]$  is orthorhombic(?) with one perfect cleavage.  $H. = 5$ .  $G. = 4$ .  $F. = 2-2.5$ . Soluble in  $HNO_3$ .  $Y$  parallel to elongation;  $Z$  normal to cleavage.  $(- )2V =$  medium,  $r < v$  moderate.  $N_X = 1.82$ ,  $N_Y = 1.86$ ,  $N_Z = 1.88$ ,  $N_Z - N_X = 0.06$ . Color emerald green. Found in the oxide zone of some copper ores, as in the Tintic district, Utah.

**Turanite**  $[Cu_5(OH)_4V_2O_8]$  is orthorhombic(?) in radiating fibers  $H. = 5$ .  $Z \parallel$  length.  $2V =$  large,  $N_X = 2.00$ ,  $N_Y = 2.01$ ,  $N_Z = 2.02$ .  $N_Z - N_X = 0.02$ . Color dark olive green with  $X =$  brown,  $Y =$  brown,  $Z =$  green. Found near Andijan, Turkestan. Compare volborthite.

**Tavistockite**  $[Ca_3Al_2(OH)_6(PO_4)_2]$  is orthorhombic in vertical needles with perfect 100 cleavage.  $F. = 7$ . Soluble in acid. The optic plane is 100;  $Z = c$ .  $(+ )2V = 74^\circ \pm$ .  $N_X = 1.522$ ,  $N_Y = 1.530$ ,  $N_Z = 1.544$ ,  $N_Z - N_X = 0.022$ . Color white. Found on quartz at Tavistock, England.

**Chlorophoenicite**  $[(Mn,Mg,Zn)_5(OH)_7AsO_4]$  is monoclinic  $^{215}$  with  $a:b:c = 2.357:1:2.153$ ,  $\beta = 105^\circ 34'$ . Crystals deeply striated and elongated parallel to  $b$ . Distinct 100 cleavage.  $H. = 3-3.5$ .  $G. = 3.4-3.6$ .  $F. = 6$ , but blackens. The optic plane is 010 and an optic axis is nearly normal to 100.  $(- )2V = 83^\circ$ ,  $r > v$  strong. With 1.34 MgO it has  $N_X = 1.682$ ,  $N_Y = 1.690$ ,  $N_Z = 1.697$ ,  $N_Z - N_X = 0.015$ . With 29.95% MgO it has  $^{93} (+ )2V =$  small,  $N_X = 1.669$ ,  $N_Y = 1.672$ ,  $N_Z = 1.677$ ,  $N_Z - N_X = 0.008$ . Color pale green in daylight and purplish red in artificial light. Found with franklinite and willemite at Franklin, New Jersey.

**Pseudomalachite**  $^{216}$  (or *dihydrate*)  $[Cu_5(OH)_4PO_4]_2$  is monoclinic with  $a:b:c = 2.962:1:0.780$ ,  $\beta = 91^\circ 2'$ . Space group  $P2_1/a$ ;  $a$  17.06,  $b$  5.76,  $c$  4.49 Å. U.C. 2. Crystals acicular or distinct or aggregates. Perfect but difficult 100 cleavage.  $H. = 4.5-5$ .  $G. = 4.1-4.3$ ,  $F. = 2-2.5$ . Soluble in HCl.  $X \wedge c = -21^\circ$  to  $-26^\circ$ ;  $Y = b$ .  $(- )2V = 50^\circ$ ,  $r > v$  strong.  $N_X = 1.789$ ,  $N_Y = 1.835$ ,  $N_Z = 1.845$ ,  $N_Z - N_X = 0.056$ . Again:  $^{51} (- )2V = 46^\circ$ ,  $N_X = 1.80$ ,  $N_Y = 1.80$ ,  $N_Z = 1.88$ ,  $N_Z - N_X = 0.08$ . Also:  $^{28} (\pm )2V = 90^\circ$ ,  $N_X = 1.719$ ,  $N_Y = 1.763$ ,  $N_Z = 1.805$ ,  $N_Z - N_X = 0.086$ ; and:  $^{217} N_X = 1.708$ ,  $N_Y = 1.753$ ,  $N_Z = 1.800$ ,  $N_Z - N_X = 0.092$ . Color dark emerald green with  $X =$  greenish blue,  $Y =$  yellowish green,  $Z =$  pale yellowish brown, and  $X < Z$ . Also:  $^{51} X =$  pale green,  $Y =$  pale yellowish green,  $Z =$  strong green. Again:  $^{217} X =$  yellowish green,  $Y =$  bluish green,  $Z =$  deep bluish green. Found in the Urals, etc. Differs from malachite in lack of effervescence with acids.

<sup>214</sup> G. Aminoff: *Svenska Vetensk. Handl.*, IX, No. 5, 52 (1931); *Strukturber.*, II, 466 (1937).

<sup>215</sup> W. F. Foshag and R. B. Gage: *Jour. Wash. Acad. Sci.*, XIV, 362 (1924); W. F. Foshag, H. Berman, and R. B. Gage: *Proc. U. S. Nat. Mus.*, LXX, Art. 20 (1927).

<sup>216</sup> L. G. Berry: *Am. Mineral.*, XXXV, 365 (1950).

<sup>217</sup> V. L. Ayres: *Am. Mineral.*, XXV, 432 (1940).

## (b) WITH ADDITIONAL ANIONS—HYDROUS

**Spherite**  $[\text{Al}_{10}(\text{OH})_{18}\text{P}_4\text{O}_{16}\cdot 7\text{H}_2\text{O}]$  is orthorhombic in fibrous concretions with one distinct cleavage.  $H. = 4$ .  $G. = 2.54$ .  $F. = 7$ . According to Slavik,<sup>218</sup> elongation negative with  $N$  (normal to elongation)  $= 1.575$ ,  $N$  (parallel to elongation)  $= 1.563$ . According to Larsen,<sup>27</sup> elongation positive with  $N_X = 1.562$ ,  $N_Y = 1.576$ ,  $N_Z = 1.588$ ,  $N_Z - N_X = 0.026$ . Color white to bluish; colorless in section. Found in hematite in schists at Zajecov, Bohemia.

**Renardite**  $[\text{Pb}(\text{UO}_2)_4(\text{OH})_4(\text{PO}_4)_2\cdot 5\text{H}_2\text{O}]$  is orthorhombic with  $a:c = 1:1.209$ . Crystals  $\{100\}$  plates with perfect 100 cleavage.  $G. > 4$ . Soluble in acids. The optic plane is 001;  $X = a$ .  $(- )2V = 70^\circ \text{ ca.}$ ,  $r > v$ .  $N_X = 1.715$ ,  $N_Y = 1.736$ ,  $N_Z = 1.739$ ,  $N_Z - N_X = 0.024$ . Color yellow with  $X = \text{colorless}$ ,  $Y$  and  $Z = \text{yellow}$ . Found with torbernite in the Belgian Congo.

**Dumontite**  $[\text{Pb}_2(\text{UO}_2)_3(\text{OH})_4(\text{PO}_4)_2\cdot 3\text{H}_2\text{O}]$  is orthorhombic with  $a:b:c = ? : 1 : 1.327$ . Crystals pinacoidal. The optic plane is 001;  $Z = a$ .  $(+)2V = \text{large}$ ,  $r < v$ .  $N_X = 1.88$ ,  $N_Y = 1.89$ ,  $N_Z = 1.90$  (calc.),  $N_Z - N_X = 0.02 \text{ ca.}$  Color yellow with  $X = \text{pale yellow}$ ,  $Y = \text{dark yellow}$ ,  $Z = ?$  Found with torbernite in the Belgian Congo.

**Crandallite**  $[\text{CaAl}_4(\text{OH})_8(\text{PO}_4)_2\cdot \text{H}_2\text{O}]$  is probably orthorhombic, with perfect 100 cleavage.  $H. = 4$ .  $G. = 2.78$ .  $F. = 2-3$ , with decrepitation. The optic plane is 010;  $X = c$ .  $(+)2V = \text{moderate}$ .  $N_X = 1.59$ ,  $N_Y = ?$ ,  $N_Z = 1.60$ ,  $N_Z - N_X = 0.01$ . Again,<sup>219</sup>  $N_X = 1.618$ ,  $N_Z = 1.620$ . Color white. Apparently an alteration product of hamlinite. Found in a quartz vein in Utah.

**Cornwallite**  $[\text{Cu}_5(\text{OH})_4(\text{AsO}_4)_2\cdot \text{H}_2\text{O}]$  is orthorhombic(?); massive in finely fibrous spherulites.  $H. = 4.5$ .  $G. = 4.16$ .  $F. = 2-2.5$ . The optic plane seems to be normal to the elongation.  $(+)2V = \text{small}$ .  $N_X = 1.81 \text{ ca.}$ ,  $N_Y = 1.815 \text{ ca.}$ ,  $N_Z = 1.85 \text{ ca.}$ ,  $N_Z - N_X = 0.04 \text{ ca.}$  Color deep green like malachite (but it does not effervesce with acids). Found on olivenite in Cornwall.

**Acrochordite**<sup>220</sup>  $[\text{Mg}(\text{MnOH})_4(\text{AsO}_4)_2\cdot 4\text{H}_2\text{O}]$  is monoclinic in very small units grouped in wartlike aggregates.  $H. = 3.5$ .  $G. = 3.19$ .  $X = b$ ;  $Z \wedge c = 45^\circ-50^\circ$ .  $(+)2V = \text{moderate}$ ,  $r < v$  distinct.  $N_X = 1.672$ ,  $N_Y = 1.676$ ,  $N_Z = 1.683$ ,  $N_Z - N_X = 0.011$ . Color yellowish brown. Found at Långban, Sweden.

5. Phosphates with type formula  $A_m\text{BX}_4$  and  $m = 3$  or more

## (a) WITHOUT ADDITIONAL ANIONS

**Stercorite** (or *microcosmic salt*)  $(\text{NH}_4\text{NaHPO}_4\cdot 4\text{H}_2\text{O})$  is pseudomonoclinic prismatic<sup>221</sup> with  $a:b:c = 2.908:1:1.859$ ,  $\beta = 98^\circ 30'$ . Crystals short prismatic without cleavage.  $H. = 2$ .  $G. = 1.57$ .  $F. = 79^\circ \text{ C.}$  Loses  $\text{NH}_3$  and  $\text{H}_2\text{O}$  between  $96^\circ$  and  $200^\circ \text{ C.}$  changing to  $\text{NaPO}_3$  which forms sodium phosphate beads of importance in blowpipe work. The optic plane is nearly normal to 010; on 001,  $X' \wedge 100 = 9^\circ 35'$ ; and on 100,  $X' \wedge 001 = 1^\circ 20'$  with strong dispersion.  $Z$  is nearly normal to 001.  $(+)2V = 35^\circ 34'$ ,  $r > v$  rather strong.  $N_X = 1.439$ ,  $N_Y = 1.442$ ,  $N_Z$

<sup>218</sup> F. Slavik: *Bull. Intern. Acad. Bohème*, XXII, 32 (1918); *Min. Abst.*, I, 290 (1921).

<sup>219</sup> S. G. Gordon: *Proc. Phila. Acad. Nat. Sci.*, XCVI, 336 (1944).

<sup>220</sup> G. Flink: *Geol. För. Förh.*, XLIV, 773 (1922).

<sup>221</sup> A. Schaschek: *Tsch. Min. Pet. Mit.*, XXXII, 402 (1913).

$= 1.469$ ,  $N_z - N_x = 0.030$ . A section parallel to 010 shows two sets of lamellar twinning at about  $90^\circ$ . Colorless. Found in guano, as on the Guanape Islands near Peru.

### (b) WITH ADDITIONAL ANIONS—ANHYDROUS

**Hematolite**  $[\text{Mn}_4\text{Al}(\text{OH})_8\text{AsO}_4]$  is hexagonal<sup>222</sup> with  $c/a = 4.415$ .  $a$  8.27,  $c$  36.51 Å. Crystals rhombohedral with perfect basal cleavage.  $H. = 3.5$ .  $G. = 3.49$ .  $F. = 7$ . Soluble in acid. Uniaxial negative with  $N_o = 1.733$ ,  $N_E = 1.714$ ,  $N_o - N_E = 0.019$ . Also biaxial with a small optic angle. Color brownish red to black; yellowish to brown and not pleochroic in section. Found in the Moss mine in Sweden.

**Holdenite**  $[(\text{Mn}, \text{Zn})_6(\text{OH})_5\text{O}_2\text{AsO}_4]$  is orthorhombic<sup>223</sup> with  $a:b:c = 0.380:1:0.276$ . Space group<sup>224</sup>  $Bmam$ ;  $a$  11.97,  $b$  31.15,  $c$  8.58 Å. Crystals 100 tablets with indistinct 010 cleavage.  $H. = 4$ .  $G. = 4.07$ . The optic plane is 010;  $Z = a$ .  $(+ )2V = 30^\circ$ ,  $r > v$  distinct.  $N_x = 1.769$ ,  $N_y = 1.770$ ,  $N_z = 1.785$ ,  $N_z - N_x = 0.016$ . Color pink to red. Found with willemite, calcite, etc., at Franklin, New Jersey.

**Lacroixite**  $[\text{Na}_4(\text{Mn}, \text{Ca})_4\text{Al}_3(\text{F}, \text{OH})_9(\text{PO}_4)_4?]$  is orthorhombic<sup>225</sup> (?) with  $a:b:c = 0.796:1:1.568$ . Crystals pyramidal with 111 and  $\bar{1}\bar{1}1$  (but not  $\bar{1}11$  and  $1\bar{1}1$ ) cleavages at an angle of  $72^\circ$ .  $H. = 4.5$ .  $G. = 3.13$ . Soluble in HCl. An uncentered optic axis is visible on one cleavage.  $2V = \text{large}$ .  $N_y = 1.57$ ,  $N_z - N_x = \text{distinct}$ . Color pale yellowish or greenish. Found in pegmatite in Saxony.

**Retzianite**<sup>226</sup>  $[(\text{Mn}, \text{Ca})_{14}\text{R}(\text{OH})_{25}(\text{AsO}_4)_2?]$  is orthorhombic with  $a:b:c = 0.441:1:0.727$ . Crystals prisms or {010} tablets, without cleavage.  $H. = 4$ .  $G. = 4.15$ .  $F. = 7$ . Soluble in acids. The optic plane is 010;  $Z = a$ .  $(+ )2V = \text{large}$ ,  $r < v$  weak.  $N_x = 1.777$ ,  $N_y = 1.788$ ,  $N_z = 1.800$ ,  $N_z - N_x = 0.023$ . Color dark chocolate to chestnut brown with  $X = \text{colorless}$ ,  $Y = \text{pale yellowish brown}$ ,  $Z = \text{reddish brown}$ . Found in the Moss mine at Nordmark, Sweden.

**Flinkite**  $[\text{Mn}_2'''\text{Mn}''(\text{OH})_4\text{AsO}_4]$  is orthorhombic with  $a:b:c = 0.413:1:0.739$ . Crystals {001} tablets, with no good cleavage.  $H. = 4-4.5$ .  $G. = 3.87$ .  $F. = \text{easy}$ . Soluble in acid. The optic plane is 001;  $Z = a$ .  $(+ )2V = \text{large}$ , with slight dispersion.  $N_x = 1.783$ ,  $N_y = 1.801$ ,  $N_z = 1.834$ ,  $N_z - N_x = 0.051$ . Color greenish brown with  $X = \text{yellowish or brownish green}$ ,  $Y = \text{yellowish green}$ ,  $Z = \text{orange-brown}$ . Found near Pajsberg, Sweden.

**Cornetite**  $[(\text{CuOH})_3\text{PO}_4]$  is orthorhombic dipyramidal with<sup>216</sup>  $a:b:c = 0.772:1:0.505$ . Space group  $Pbca$ ;  $a$  10.88,  $b$  14.10,  $c$  7.11 Å. U.C. 8. Crystals equant with {210}, {021}, etc.  $H. = 5$ .  $G. = 4.1$ . Soluble in HCl. The optic plane<sup>227</sup> is 100;  $X = b$ .  $(- )2V = 33^\circ$  (Tl),<sup>28</sup>  $2E = 62^\circ$ ,  $r < v$  strong,  $N_x = 1.765$ ,  $N_y = 1.81$ ,  $N_z = 1.82$ ,  $N_z - N_x = 0.055$ . Again:<sup>51</sup>  $N_x = 1.762$ ,  $N_y = 1.820$ ,  $N_z = 1.825$ ,  $N_z - N_x = 0.063$ . Also:<sup>228</sup>  $N_x = 1.765$ ,  $N_y > 1.79$  and  $< 1.80$ ,  $N_z > 1.83$  and  $< 1.84$ . Color peacock to greenish blue; not perceptibly pleochroic. Zonal growth not rare. Found in the Belgian Congo and Rhodesia.

<sup>222</sup> L. G. Berry and A. R. Graham: *Am. Mineral.*, XXXIII, 489 (1948).

<sup>223</sup> C. Palache and E. V. Shannon: *Am. Mineral.*, XII, 144 (1927).

<sup>224</sup> J. Prewitt-Hopkins: *Am. Mineral.*, XXXIV, 589 (1949).

<sup>225</sup> F. Slavik: *Bull. Int. Acad. Sci. Bohème*, XX, 372 (1916).

<sup>226</sup> In the formula R stands for rare earths.

<sup>227</sup> A. Hutchinson and A. M. Macgregor [*Mineral. Mag.*, XIX, 225 (1921)] orient the crystals so that  $X = a$  and  $Y = c$ .

<sup>228</sup> A. Schoep: *Mineral. Abst.*, III, 552 (1926).



**Georgiadesite**  $[(\text{PbCl})_3\text{AsO}_4]$  is orthorhombic with  $a:b:c = 0.577:1:0.223$ . Crystals small, pseudo-hexagonal, without cleavage.  $H. = 3.5$ .  $G. = 7.1$ .  $F. =$  easy. Soluble in  $\text{HNO}_3$ . The optic plane is 100;  $X = b$ .  $(+ )2V =$  large.  $N = 2.1$  (est.),  $N_Z - N_X =$  distinct. Color white to yellow. Found on lead slag at Laurium, Greece.

**Tyrolite** <sup>229</sup>  $[(\text{Cu,Ca})_6\text{CO}_3(\text{OH})_4\{\text{As}(\text{O,S})_4\}_2]$  is orthorhombic dipyramidal;  $a:b:c = 0.192:1:0.102$ . Space group probably  $Pmma$ ;  $a$  10.5,  $b$  54.7,  $c$  5.59 Å. Crystals {010} plates elongated along  $a$ ; radiated laminae. Perfect 010 cleavage.  $H. = 1-1.5$ .  $G. = 2.27$ .  $F. = 2-2.5$ . Soluble in  $\text{HNO}_3$  or  $\text{NH}_4\text{OH}$ . The optic plane is 001;  $X = b$ .  $(- )2V = 36^\circ$ ,  $r > v$ , strong.  $N_X = 1.694$ ,  $N_Y = 1.726$ ,  $N_Z = 1.730$ ,  $N_Z - N_X = 0.036$ . Color pale green to sky blue with  $X =$  grass green,  $Y =$  yellowish green,  $Z =$  grass green. Found in copper-ore deposits in the Urals.

**Bradleyite**  $(\text{MgCO}_3 \cdot \text{Na}_3\text{PO}_4)$  is probably biaxial,<sup>230</sup> but is known only in very fine-grained masses.  $G. = 2.73$ .  $N_X = 1.49$ ,  $N_Y = ?$ ,  $N_Z = 1.56$ ,  $N_Z - N_X = 0.07$ . Again:<sup>231</sup>  $(- )2V =$  small,  $N_X = 1.477$ ,  $N_Z = 1.540$ ,  $N_Z - N_X = 0.063$ . Found in an oil well in Wyoming with clay and shortite.

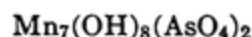
**Clinoclasite**  $[(\text{CuOH})_3\text{AsO}_4]$  is monoclinic prismatic with  $a:b:c = 1.911:1:1.122$ ,  $\beta = 99^\circ 22'$ . Space group <sup>232</sup>  $P2_1/c$ .  $a$  12.33,  $b$  6.42,  $c$  7.21 Å. U.C. 4. Crystals prismatic or basal tablets with perfect basal cleavage.  $H. = 3$ .  $G. = 4.38$ .  $F. = 2-2.5$ . Soluble in  $\text{HNO}_3$ . The optic plane is 010;  $Z$  is very near  $a$ .  $(- )2V = 53^\circ$ ;  $N_X = 1.756$ ,  $N_Y = 1.874$ ,  $N_Z = 1.896$ ,  $N_Z - N_X = 0.14$ . Color black blue-green, with  $X =$  pale blue-green,  $Y =$  light blue-green,  $Z =$  benzol green. Found in the oxide zone of copper deposits, as in the Tintic district, Utah.

**Atelestite**  $[\text{Bi}_3(\text{OH})_2\text{O}_4\text{AsO}_4]$  is monoclinic with <sup>233</sup>  $a:b:c = 0.933:1:1.505$ ,  $\beta = 99^\circ 17'$ . Indistinct 001 cleavage.  $H. = 3-4.5$ .  $G. = 6.4$ .  $F. = 1.5$ .  $(+ )2V = 44^\circ$ ,  $r < v$  rather strong.  $N_X = 2.14$ ,  $N_Y = 2.15$ ,  $N_Z = 2.18$ ,  $N_Z - N_X = 0.04$ . Color sulfur yellow. Found in a mine at Schneeberg, Saxony.

**Azovskite** <sup>234</sup>  $[\text{Fe}_3(\text{OH})_6\text{PO}_4]$  has conchoidal fracture;  $H. = 4$ .  $G. = 2.5$ . Easily soluble in  $\text{HCl}$ . Weakly birefringent with  $N =$  about 1.758. Color dark brown with brown streak and tarry luster. Found in veinlets in iron ores near Azov Sea, Russia.

**ALLACTITE** <sup>235</sup>

## MONOCLINIC PRISMATIC



$$a:b:c = 0.821:1:0.451 \quad \beta = 95^\circ 37'$$

**PHYS. CHAR.** Crystals prismatic or {100} tablets. Distinct  $\bar{1}01$ , fair 010, and poor 100 cleavages.  $H. = 4.5$ .  $G. = 3.84$ .  $F. = 6$ . Soluble in acid.

**OPT. PROP.** The optic plane is normal to 010 for red and yellow and parallel to 010 for blue.  $X \wedge c = -49^\circ$  (to  $-51^\circ$ ) for all colors.  $(- )2V = 8^\circ 56'$  B,  $4^\circ 0'$  D,  $0^\circ$  (573  $m\mu$ ),  $8^\circ 23'$  E,  $11^\circ 22'$  F.  $N_Z = 1.779$  Na (Aminoff <sup>235</sup>);  $N_X = 1.761$ ,

<sup>229</sup> Formula given as  $\text{Cu}_9\text{Ca}_2(\text{OH})_{10}(\text{AsO}_4)_4 \cdot 10\text{H}_2\text{O}$  by L. G. Berry: *Bull. Geol. Soc. Am.*, LVIII, 1168 (1947); he also gives X-ray data.

<sup>230</sup> J. J. Fahey and G. Tunell: *Am. Mineral.*, XXVI, 646 (1941).

<sup>231</sup> H. Brasseur: *Bull. Soc. Sci. Liège*, XV, 527 (1946).

<sup>232</sup> C. Palache and L. G. Berry: *Am. Mineral.*, XXXI, 243 (1946).

<sup>233</sup> H. Strunz: *Mineral. Tabellen*, p. 156 (1941).

<sup>234</sup> N. E. Efremov: *Am. Mineral.*, XXIII, 667 (1938). *Min. Abst.*, VII, 59 (1938).

<sup>235</sup> G. Aminoff: *Geol. För. Förh.*, XLIII, 24 (1921).



$N_Y = 1.786$ ,  $N_Z = 1.787$ ,  $N_Z - N_X = 0.026$  (Larsen<sup>27</sup>);  $N_X = 1.755$ ,  $N_Y = 1.772$ ,  $N_Z = 1.774$ ,  $N_Z - N_X = 0.019$  (Palache and Berman<sup>236</sup>).  $F - C$  for  $N_Y = 0.0204$ .

Color brownish red with  $X$  = pale sea green,  $Y$  and  $Z$  = yellowish green to pale yellow.

**OCCUR.** Found at Långban and Nordmark, Sweden.

**Ježekite**  $[Na_4CaAl_2(OH)_4O(PO_4)_2]$  is monoclinic with  $a:b:c = 0.896:1:1.024$ ,  $\beta = 105^\circ 31'$ . Crystals prismatic or {100} tablets with perfect 100 and imperfect 001 cleavages.  $H. = 4.5$ .  $G. = 2.94$ . The optic plane is 010;  $X \wedge c = -29^\circ$ .  $(- )2V = \text{medium}$ ,  $N_X = 1.55$ ,  $N_Y = 1.58(?)$ ,  $N_Z = 1.59$ ,  $N_Z - N_X = 0.04$ . Colorless. Found in pegmatite at Ehrenfriedersdorf, Saxony.

**Synadelphite**<sup>237</sup>  $[Mn_4(OH)_5AsO_4]$  is triclinic with  $a:b:c = 0.533:1:0.585$ ,  $\alpha$ ,  $\beta$ , and  $\gamma$  all near  $90^\circ$ ; so the mineral is nearly orthorhombic.  $a$  9.91,  $b$  18.70,  $c$  10.65 Å. U.C. 10. Crystals prismatic or pyramidal with poor 010 cleavage.  $H. = 4.5$ .  $G. = 3.57$ .  $F. = \text{easy}$ . Soluble in HCl.  $X$  is at  $\phi = -8^\circ$ ,  $\rho = 86^\circ$ ,  $Y$  at  $\phi = -172^\circ$ ,  $\rho = 86^\circ$ ,  $Z$  at  $\phi = 42^\circ$ ,  $\rho = 7^\circ$ .  $(+)2V = 37^\circ$ ,  $r > v$ .  $N_X = 1.750$ ,  $N_Y = 1.751$ ,  $N_Z = 1.761$ ,  $N_Z - N_X = 0.011$ . Brownish with  $X$  and  $Y$  = colorless,  $Z$  = light brown; but always coated with a red film, and so in mass red or dark brown. This red coating contains about 3% PbO and has been called *plumbosynadelphite*.<sup>237</sup>  $H. = 4$ .  $G. = 3.79$ .  $(+)2V = 40^\circ$ ,  $N_X = 1.851$ ,  $N_Y = 1.864$ ,  $N_Z = 1.894$ ,  $N_Z - N_X = 0.043$ . Color dark brown or red to black with  $X$  = light brown,  $Y$  = brown,  $Z$  = dark red-brown. Found at the Moss mine, Nordmark, Sweden.

**Walpurgite**  $[Bi_{10}(UO_2)_3(OH)_{24}(AsO_4)_4?]$  is triclinic with  $a:b:c$ <sup>238</sup> =  $0.691:1:1.533$ ,  $\alpha = 118^\circ 10'$ ,  $\beta = 113^\circ 9'$ ,  $\gamma = 95^\circ 37'$ . Crystals {010} tablets vertically elongated. Twinned on 010.  $H. = 3.5$ .  $G. = 5.8$ .  $F. = 1.5$ .  $X$  nearly normal to 010. Maximum extinction is at  $8^\circ$  to  $c$  in the zone normal to 010. In 010,  $Y \wedge c = 12^\circ$ .  $(- )2V = 52^\circ$  ca.  $N_X = 1.90$ ,  $N_Y = 2.00$ ,  $N_Z = 2.05$ ,  $N_Z - N_X = 0.15$ . Other measures give:  $N_X = 1.871$ ,  $N_Y = 1.975$  and  $2.01$ ,  $N_Z = 2.005$  and  $2.03$ ,  $N_Z - N_X = 0.134$ . Color wax yellow. Found in ore deposits near Schneeberg, Saxony.

**Borickite**  $[Ca_3Fe'''_{14}(OH)_{30}(PO_4)_4?]$  is apparently amorphous.  $H. = 3.5$ .  $G. = 2.7 \pm$ .  $F. = 3-4$ . Soluble in acid. Isotropic with  $N = 1.57-1.67$ . Color reddish brown. Found in schist at Nenacovic, Bohemia. *Fouchérite*<sup>239</sup> is similar, if not identical;  $N = 1.61-1.67$ .

## (b) WITH ADDITIONAL ANIONS—HYDROUS

**Freirinite**<sup>240</sup>  $[Na_{12}Ca_3Cu_9(OH)_{12}(AsO_4)_8 \cdot 6H_2O?]$  is probably tetragonal, with perfect basal and indistinct 110 cleavages.  $G. = 3.32$ .  $F. = \text{easy}$ . Soluble in HCl. Uniaxial negative with  $N_O = 1.748$ ,  $N_E = 1.645$ ,  $N_O - N_E = 0.103$ . Color greenish blue with  $X < Z$ . Found in cobalt ores at San Juan, Chile.

**Chalcophyllite**  $[(Cu_{18}Al_2(OH)_{27}(SO_4)_3(AsO_4)_3 \cdot 36H_2O?]$  is hexagonal scalenohedral<sup>241</sup> with  $c/a = 5.351$ . Space group  $R\bar{3}m$ ;  $a$  10.75,  $c$  57.40 Å. U.C. 1. Crystals

<sup>236</sup> C. Palache and H. Berman: *Min. Abst.*, V, 517 (1934); they give a new orientation with  $a:b:c = 0.901:1:0.449$ ,  $\beta = 114^\circ 4'$ .

<sup>237</sup> C. S. Hurlbut: *Am. Mineral.*, XXII, 526 (1937).

<sup>238</sup> E. Fischer: *Zeit. Krist.*, CVI, 25 (1945).

<sup>239</sup> F. Slavik: *Bull. Int. Acad. Sci. Bohème*, XXII, 32 (1918); A. Orlov: *Min. Abst.*, IV, 516 (1931); A. Lacroix: *Minéral. France*, IV, 535 (1910).

<sup>240</sup> W. F. Foshag: *Am. Mineral.*, IX, 30 (1924).

<sup>241</sup> L. G. Berry and H. R. Steacy: *Bull. Geol. Soc. Am.*, LVII, 1178 (1946).

basal tablets with perfect basal cleavage.  $H. = 2$ .  $G. = 2.67$ .  $F. = 2-2.5$ . Soluble in  $HNO_3$ . Uniaxial negative with  $N_O = 1.632$ ,  $N_E = 1.575$ ,  $N_O - N_E = 0.057$  (Gaubert<sup>242</sup>);  $N_O = 1.618$ ,  $N_E = 1.552$ ,  $N_O - N_E = 0.066$  (Shannon<sup>243</sup>); loses water easily with increase in indices; thus, after a few hours in a desiccator,  $N_O = 1.680$ ,  $N_E = 1.620$ ,  $N_O - N_E = 0.060$ . Color emerald green. Found in copper deposits as in the Tintic district, Utah.

**Hemafibrite**  $[(MnOH)_3AsO_4 \cdot H_2O]$  is orthorhombic with  $a:b:c = 0.526:1:1.150$ . Crystals prismatic to fibrous, with distinct 010 cleavage.  $H. = 3$ .  $G. = 3.6$ .  $F. =$  easy, to black bead. Soluble in  $HCl$ . The optic plane is 100;  $X = b$ .  $(+)2V = 35^\circ$ ,  $r > v$ .  $N_X = 1.87$ ,  $N_Y = 1.88$ ,  $N_Z = 1.93$ ,  $N_Z - N_X = 0.06$ . Color greenish to garnet red; alters to black. In section red-brown, not pleochroic. Found in the Moss mine, Nordmark, Sweden.

**Tinticite**  $[Fe_3(OH)_3PO_4 \cdot 3.5H_2O]$  is probably orthorhombic.<sup>244</sup> Crystals are oblong tablets which vary from 0.3 to 1.67 microns in greatest dimension.  $H. =$  about 2.5.  $G. = 2.82$ . Mean index is 1.745 and  $N_Z - N_X = 0.005-0.007$ . Creamy white color, slightly yellowish. Found in a limestone cave near Tintic, Utah.

**Veszelyite**  $\{[(Zn,Cu)OH]_3(P,As)O_4 \cdot 2H_2O\}$  is monoclinic<sup>245</sup> with  $a:b:c = 0.729:1:0.954$ ,  $\beta = 103^\circ 23'$ .  $H. = 3.5-4$ .  $G. = 3.34$ . Fusible. No cleavage. The optic plane is 010;  $Z \wedge c = +39^\circ (23^\circ)$ .  $(+)2V = 71^\circ$ ,  $r < v$  very strong.  $N_X = 1.640$ ,  $N_Y = 1.658$ ,  $N_Z = 1.695$ ,  $N_Z - N_X = 0.055$ . Color greenish blue; not pleochroic. Found at Morawitza in the Banat.

A very similar mineral<sup>246</sup> found in Rhodesia is monoclinic with  $a:b:c = 0.71:1:0.95$ ,  $\beta = 103.5^\circ$ . No good cleavage.  $H. = 3.5-4$ .  $G. > 3.33$ . Soluble in  $HCl$ . The optic plane is 010;  $Z \wedge c = +33^\circ$ .  $(+)2H = 43^\circ$ ,  $r < v$ .  $N_Y = 1.63$  ca.  $N_Z - N_X =$  strong. Color a fine blue; not pleochroic. Lamellar twinning.

**Arakawaite**  $[ZnCu_2(OH)_3PO_4 \cdot 2H_2O]$  is much like veszelyite; it is monoclinic with  $a:b:c = 0.75:1:1.024$ ,  $\beta = 109.5^\circ$ .  $H. = 3.5$ .  $G. = 3.09$ . The optic plane is 010;  $Z \wedge c = +36^\circ$ .  $(+)2V = 38.5^\circ$ ;  $N_X = 1.618$ ,  $N_Y = 1.622$ ,  $N_Z = 1.658$ ,  $N_Z - N_X = 0.040$ . Color dark bluish green. Found in ore deposits near Akita, Japan.

**Liskeardite**  $[(Al,Fe)_3(OH)_6AsO_4 \cdot 5H_2O]$  is monoclinic(?) in fibrous crusts with good 010 cleavage.  $H. = 4$  ca.  $G. = 3$ .  $F. = 7$ . Insoluble in  $HNO_3$ .  $Y = b$ ;  $Z \wedge 001 = 70^\circ \pm$  (Lacroix<sup>247</sup>);  $Z = c$  (Larsen<sup>27</sup>):  $(+)2E = 115^\circ$  (Lacroix<sup>247</sup>);  $2V =$  near  $90^\circ$  (Larsen<sup>27</sup>);  $N_X = 1.661$ ,  $N_Y = 1.675$ ,  $N_Z = 1.689$ ,  $N_Z - N_X = 0.028$ . Color white. Found in the oxide zone of ore at Liskeard, Cornwall.

**Tsumebite**  $[CuPb_2(OH)_3PO_4 \cdot 3H_2O]$  is monoclinic<sup>247</sup> with  $a:b:c = 0.655:1:0.675$ ,  $\beta = 94^\circ 22'$ . Crystals {101} plates with {100}, {110}, etc.  $H. = 3.5$ .  $G. = 6.1$ . Soluble in  $HCl$ .  $(+)2V = 89^\circ$ ,  $r < v$  strong.  $N_X = 1.885$ ,  $N_Y = 1.920$ ,  $N_Z = 1.956$ ,  $N_Z - N_X = 0.071$ . Color emerald green. Faintly absorptive with  $X < Z$ . Found in an ore deposit at Tsumeb, Southwest Africa.

**Liroconite**  $[Cu_2Al(OH)_4(As,P)O_4 \cdot 4H_2O]$  is monoclinic prismatic<sup>248</sup> with  $a:b:c = 1.679:1:1.306$ ,  $\beta = 91^\circ 23'$ . Space group  $I2/a$ ;  $a$  12.67,  $b$  7.55,  $c$  9.86 Å. U.C. 4. Crystals have {011} and {110} faces, with indistinct 110 and 011 cleavages.  $H. =$

<sup>242</sup> P. Gaubert: *Bull. Soc. Fr. Min.*, XXVII, 222 (1904).

<sup>243</sup> E. V. Shannon: *Am. Jour. Sci.*, CCVII, 31 (1924).

<sup>244</sup> B. Stringham: *Am. Mineral.*, XXXI, 395 (1946).

<sup>245</sup> V. Zsivny: *Zeit. Krist.*, LXXXII, 87 (1932).

<sup>246</sup> F. P. Mennell: *Mineral. Mag.*, XIX, 69 (1920).

<sup>247</sup> L. LaForge: *Am. Mineral.*, XXIII, 772 (1938).

<sup>248</sup> L. G. Berry and T. Davies: *Bull. Geol. Soc. Am.*, LVII, 1178 (1946).

2-2.5.  $G. = 3.0$ .  $F. = 3-3.5$ . Soluble in  $HNO_3$ . The optic plane is normal to 010;  $Z \wedge c = +25^\circ$ .  $(- )2V = 67^\circ$ ,  $r < v$  moderate.  $N_X = 1.612$ ,  $N_Y = 1.652$ ,  $N_Z = 1.675$ ,  $N_Z - N_X = 0.063$ . Color sky blue to green; in section greenish and not pleochroic. Found in copper deposits as at Wheal Gorland, Cornwall.

**Evansite**  $[Al(OH)_2]_6(PO_4)_2 \cdot 12H_2O$  is apparently amorphous in concretions.  $H. = 4$ .  $G. = 1.94$ .  $F. = 7$ . Soluble in hot  $H_2SO_4$ . Isotropic <sup>249</sup> with  $N = 1.485$ . Colorless. Found on limonite in Hungary.

**Rosiéresite** (hydrous phosphate of Al, Pb, Cu) is related to evansite; apparently amorphous.  $G. = 2.2$ .  $F. = 7$ , but blackens. Soluble in  $HNO_3$ . Isotropic with  $N = 1.5$ . Color yellow. Found as stalactites in an abandoned copper mine.

**Kehoeite**  $[CaZn_2Al_4(OH)_{12}(PO_4)_2 \cdot 21H_2O]$  is apparently amorphous and chalky.  $G. = 2.34$ .  $F. = 7$ . Soluble in acid. Isotropic with  $N = 1.53$ . Color white. Found in the Meritt mine in South Dakota.

## 6. Phosphates with type formula $A_2B_2X_7$

**Roméite**  $[(Na,Ca,Mn)_2Sb_2O_6(OH,F)]$  or *atopite* is isometric hexoctahedral with 111 cleavage. Space group <sup>250</sup>  $Fd3m$ ;  $a$  10.26 Å. U.C. 8.  $H. = 5.5-6$ .  $G. = 5.1$ .  $F. = 6$ . Insoluble in acid. Isotropic with  $N = 1.82-2.21$ , with strong dispersion,  $N_F - N_C = 0.026$ . Also uniaxial positive (Lacroix), an octahedron being composed of eight segments; four seen in a 100 section extinguish parallel to the edges. Each segment may show lamellar twinning with weak birefringence, apparently biaxial negative (Larsen <sup>27</sup>). The index decreases with increase of sodium replacing calcium. Color yellow. Found at San Marcel in Piedmont.

**Weslienite** is a variety of roméite rich in fluorine. Isotropic with  $N = 2.21$ ; also biaxial, optically positive with large optic angle, undulatory extinction, and abnormal blue interference colors. Color yellow to brown; in section grayish yellow to wax yellow, in zones. Found in ore deposits.

**Lewisite**  $[(Na,Ca,Fe)_2(Sb,Ti)_2O_6(O,OH)]$  is isometric with distinct 111 cleavage. Space group <sup>251</sup>  $Fd3m$ ;  $a$  10.27 Å. U.C. 8.  $H. = 5.5$ .  $G. = 4.95$ .  $F. =$  easy. Insoluble in acid. Isotropic with  $N = 2.20$ . Color yellow to brown. Found in gravel of a mercury mine in Minas Gerães, Brazil.

**Bindheimite**  $(Pb_2Sb_2O_7 \cdot nH_2O)$  is isometric hexoctahedral and closely related to roméite (when anisotropic?). Space group <sup>252</sup>  $Fd3m$ ;  $a$  10.41 Å. U.C. 8.  $H. = 4$ .  $G. = 4.6-5$ .  $F. = 3-4$ . Isotropic with  $N = 1.86$  ca. Also anisotropic with perfect prismatic cleavage and uniaxial negative with  $N_O = 2.08$ ,  $N_E = 1.82$ ,  $N_O - N_E = 0.26$ . Color gray, green, brown. Found in the oxide zone of antimony deposits, as in Sevier County, Arkansas.

**Tripuhyite**  $(Fe_2Sb_2O_7)$  is microcrystalline.  $G. = 5.82$ .  $F. = 4-5$ .  $(+)2V =$  small,  $r < v$  very strong.  $N_X = 2.19$ ,  $N_Y = 2.20$ ,  $N_Z = 2.33$ ,  $N_Z - N_X = 0.14$ . Color dull greenish yellow. In section canary yellow. Found in cinnabar-bearing gravels of Tripuhy, Minas Gerães, Brazil.

<sup>249</sup> A sample with 40.0  $Al_2O_3$ , 13.7  $P_2O_5$ , 39.4  $H_2O$ , 1.3  $CaO$ , and 6.5  $SiO_2$  is weakly anisotropic. See R. Herzenberg: *Tech. Bull. Univ. Oruro*, 1 (1946).

<sup>250</sup> G. Natta and M. Baccaredda: *Rend. Accad. Lincei*, XV, 389 (1932); O. Zedlitz: *Zeit. Krist.*, LXXXI, 253 (1931).

<sup>251</sup> F. Machatschki and O. Zedlitz: *Zeit. Krist.*, LXXXII, 72 (1932).

<sup>252</sup> G. Hägele: *Zent. Mineral.*, 1937A, 45.

## 7. Phosphates with type formula $A_m(BX_3)_n$

**Trippkeite** ( $Cu_3As_2O_6?$ ) is tetragonal with  $c/a = 0.916$ . Crystals pyramidal with perfect 100 and poor 110 cleavages; break easily into flexible fragments like asbestos. Soft. F. = easy. Easily soluble in acid. Uniaxial positive with  $N_O = 1.90$ ,  $N_E = 2.12$ ,  $N_E - N_O = 0.22$ . Color bluish green, not pleochroic. When heated in a closed tube it changes color, first to emerald green, then to brownish and finally to yellowish green. Found in druses in copper deposits at Copiapo, Chile.

**Ecdemite** ( $Pb_6OClAs_2O_6$ ) is tetragonal in acute pyramids or basal tablets with distinct basal cleavage. H. = 2.5. G. = 6.9–7.1. F. = easy. Soluble in  $HNO_3$ . Uniaxial negative with  $N_O = 2.32$  Li,  $N_E = 2.25$ ,  $N_O - N_E = 0.07$ . Color yellow or green. Also biaxial with two or more sets of lamellar twinning; this may be another phase; it is called *heliophyllite* and described as orthorhombic with  $a:b:c = 0.967:1:2.205$ ; it is isomorphous with *ochrolite*. Found in ore deposits at Långban, Sweden.

**Finnemanite**<sup>253</sup> [ $Pb_5Cl(AsO_3)_3$ ] is hexagonal (di?)pyramidal<sup>254</sup> with  $c/a = 0.688$ .  $a$  10.21,  $c$  6.97 Å. U.C. 2. Crystals prismatic with distinct 10 $\bar{1}$ 1 cleavage. H. = 2.5. G. = 7.26. Uniaxial negative with  $N_O = 2.295$ ,  $N_E = 2.285$ ,  $N_O - N_E = 0.01$ ; F – C for  $N_O = 0.0909$ . Color olive green. Found with hematite in ore deposits at Långban, Sweden.

**Dixenite**<sup>255</sup> [ $Mn_5(OH)_2SiAs_2O_9$ ] is hexagonal and scaly with perfect basal cleavage. H. = 3–4. G. = 4.2. Decomposed by HCl. Uniaxial positive with  $N_O = 1.96$ ,  $N_E - N_O = ?$  Color black; glowing red in transmitted light; in thin section orange-yellow, not pleochroic. Found in hematite or dolomite at Långban, Sweden.

**Hewettite**<sup>256</sup> [ $H_4Ca(VO_3)_6 \cdot 7H_2O?$ ] is orthorhombic in slender blades. G. = 2.55. F. = easy, to a red liquid. On heating, loses water and changes color through shades of brown to bronze. Loss of  $6H_2O$  does not destroy the crystal. Slightly soluble in water. Z parallel to elongation. (–)2V = moderate.  $N_X = 1.77$ ,  $N_Y = 2.18$ ,  $N_Z = 2.35$  (to 2.4),  $N_Z - N_X = 0.58$ . Color deep red with X and Y = very light orange-yellow, Z = dark red. Found in the oxide zone of vanadium deposits at Minasragra, Peru.

**Metaheewettite**<sup>256</sup> has the same composition; it is orthorhombic(?) with  $a:b = 0.65:1$ . G. = 2.51. F. = easy. On heating, loses water and changes from dark red to yellow-brown. Loss of  $6H_2O$  does not destroy the crystal. Crystals are broad blades with X normal to blades and Z parallel to elongation. (–)2V = 52°.  $N_X = 1.70$ ,  $N_Y = 2.10$ ,  $N_Z = 2.33$  ca.,  $N_Z - N_X = 0.53$  ca. Color red with X = light orange-yellow, Y = deep red, Z = deeper red. Found with hewettite.

**Pascoite** [ $H_2Ca_2(VO_3)_6 \cdot 10H_2O(?)$ ] is monoclinic with poor 010 cleavage. H. = 2.5. G. = 2.46. F. = easy, to deep red liquid. Easily soluble in water. X = b; strong crossed dispersion, Z in Li light making an angle of about 8° with Z in Na light. (–)2V = 56° Li, 50° 30' Na.  $N_X = 1.775$ ,  $N_Y = 1.815$ ,  $N_Z = 1.825$ ,  $N_Z - N_X = 0.050$ . Sections normal to X give no extinction and abnormal green and orange interference colors on account of the strong dispersion. Color orange,

<sup>253</sup> G. Aminoff: *Geol. För. Förh.*, XLV, 160 (1923).

<sup>254</sup> G. Aminoff and A. L. Pargas: *Geol. För. Förh.*, XLIX, 438 (1927).

<sup>255</sup> G. Flink: *Geol. För. Förh.*, XLII, 436 (1920).

<sup>256</sup> W. F. Hillebrand, H. E. Merwin, and F. E. Wright: *Proc. Am. Phil. Soc.*, LIII, 31 (1914); *Zeit. Krist.*, LIV, 209 (1914).

with X = light cadmium yellow, Y = cadmium yellow, Z = orange. Found in the oxide zone of vanadium deposits near Pasco, Peru.

**Trigonite** <sup>255</sup>  $[HMnPb_3(AsO_3)_3]$  is monoclinic domatic with  $a:b:c = 1.074:1:1.659$ ,  $\beta = 91^\circ 31'$ . Crystals wedge-shaped, with perfect 010 and good 101 cleavages. H. = 2-3. G. = 8.28. Soluble in acid.  $X \wedge c = 45^\circ$ ;  $Y = b$ . Optic sign unknown.  $N_X = 2.08$ ,  $N_Y = 2.1$  ca.,  $N_Z = 2.16$ ,  $N_Z - N_X = 0.08$ . Color sulfur yellow to brownish. Found in dolomite with native lead at Långban, Sweden.

## X. SILICATES

X-ray studies have proved that in silicates each silicon atom is surrounded by four oxygen atoms arranged at the corners of a tetrahedron, as illustrated in Figs. 122 and 123. In Fig. 122 the silicon and oxygen atoms are assumed to be of the same size, so as to show their relative positions more plainly. Actually, the oxygen atoms are much larger than the silicon atoms, as shown in Fig. 123. If such tetrahedral groups are not linked directly by sharing one (or more) oxygen atoms, the formula of the substance will include one or more  $\text{SiO}_4$  groups<sup>1</sup> as in zircon,  $\text{ZrSiO}_4$ , and forsterite,  $\text{Mg}_2\text{SiO}_4$ . No  $\text{SiO}_4$  tetrahedron is linked to a neighboring tetrahedron by sharing more than one oxygen atom, but one tetrahedron may be thus linked to one, two, three, or four other tetrahedrons. If it is linked to only one other, as shown in Figs. 124 and 125, the formula must contain  $\text{Si}_2\text{O}_7$ , as in thortveitite,  $\text{Sc}_2\text{Si}_2\text{O}_7$ , and åkermanite,  $\text{Ca}_2\text{MgSi}_2\text{O}_7$ . If it is linked to two other tetrahedrons it may form a trigonal ring as in benitoite,  $\text{BaTiSi}_3\text{O}_9$  (Fig. 126), or a tetragonal ring (Fig. 127), or a hexagonal ring as in beryl,  $\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$  (Fig. 128); finally, it may form a continuous chain as in enstatite,  $\text{MgSiO}_3$  (Fig. 129); in all these examples the formula includes  $\text{SiO}_3$  or a multiple thereof.

If the  $\text{SiO}_4$  tetrahedron is linked to three other tetrahedrons, it forms a continuous sheet, as in micas (Fig. 130), and the formula includes  $\text{Si}_2\text{O}_5$  or a multiple. Finally, if it is linked to four other tetrahedrons, it forms a continuous three-dimensional framework as in sodalite (Fig. 131), and the formula must include  $\text{SiO}_2$  or some multiple thereof. No other cases are possible except that all tetrahedrons in a single crystal are not necessarily linked to their neighbors in the same way; this will

<sup>1</sup> A few silicates (called "subsiliates") contain one or more oxygen atoms not directly connected with a silicon atom, as in sillimanite,  $\text{AlOAlSiO}_4$ , and kornepine,  $\text{Mg}(\text{AlO})_2\text{AlSiO}_4$ .



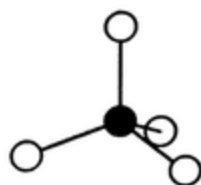


FIG. 122. A tetrahedral group of oxygen atoms around a silicon atom ( $\text{SiO}_4$ ).

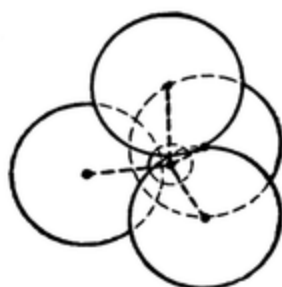


FIG. 123. A tetrahedral  $\text{SiO}_4$  group (Si at the center) with correct relative sizes of atoms.

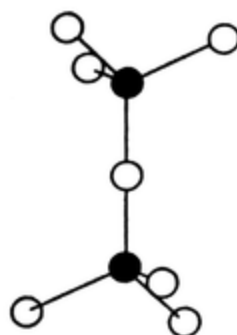


FIG. 124. Two tetrahedral  $\text{SiO}_4$  groups having one oxygen atom in common.

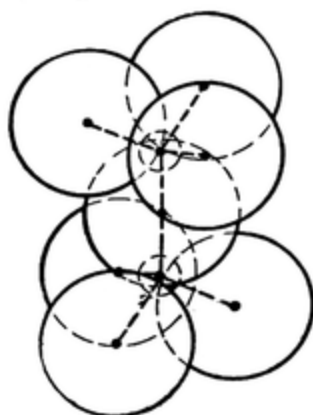


FIG. 125. Two tetrahedral  $\text{SiO}_4$  groups having one oxygen atom in common.

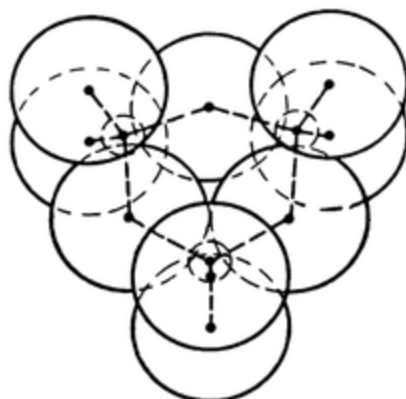


FIG. 126. Three  $\text{SiO}_4$  groups forming a trigonal ring ( $\text{Si}_3\text{O}_9$ ).

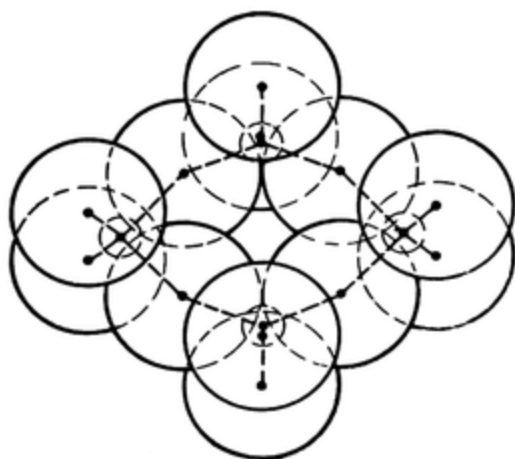


FIG. 127. Four  $\text{SiO}_4$  groups forming a tetragonal ring ( $\text{Si}_4\text{O}_{12}$ ).

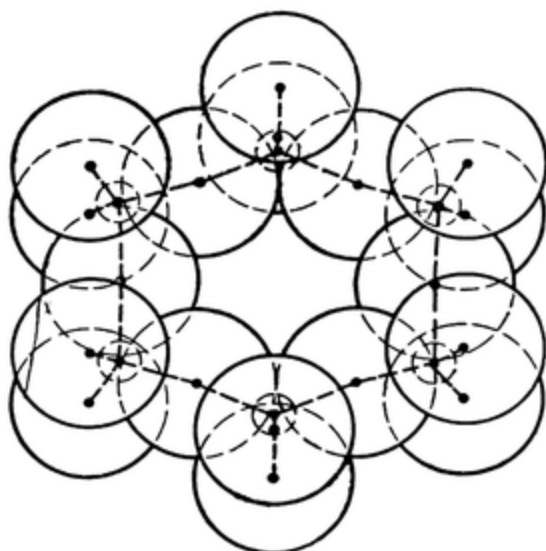


FIG. 128. Six  $\text{SiO}_4$  groups forming a hexagonal ring ( $\text{Si}_6\text{O}_{18}$ ).

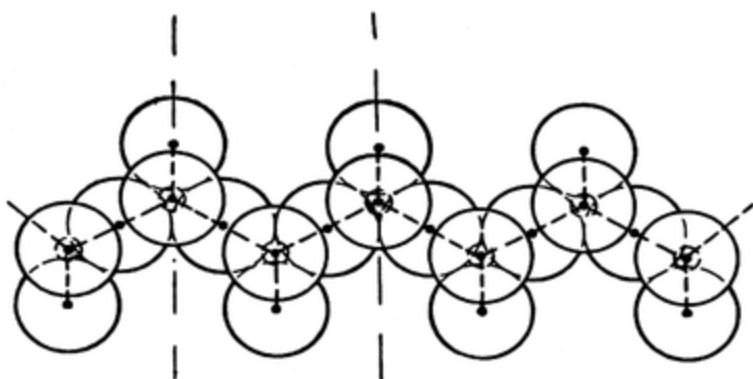


FIG. 129.  $\text{SiO}_4$  groups forming a continuous chain  $(\text{SiO}_3)_n$ .

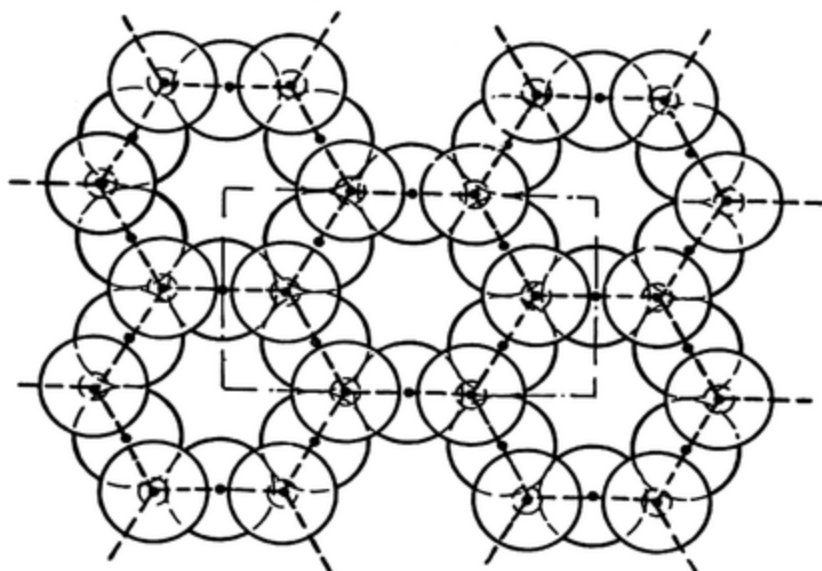


FIG. 130.  $\text{SiO}_4$  groups forming a continuous sheet  $(\text{Si}_2\text{O}_5)_n$ .



FIG. 131.  $\text{SiO}_4$  groups (sketched in perspective) forming a continuous three-dimensional framework  $(\text{SiO}_2)_n$ . After Jaeger.

be described later. On this basis silicates may be classified as follows:<sup>2</sup>

Class	Grouping of SiO <sub>4</sub> Tetra- hedrons	Linkages of SiO <sub>4</sub> Tetra- hedrons	Oxygen Atoms per 4 Si	Example  Formula	Mineral
I. Nesosilicates	Singles	0	16	Mg <sub>2</sub> SiO <sub>4</sub>	Forsterite
II. Sorosilicates	Groups	1	14	Ca <sub>2</sub> MgSi <sub>2</sub> O <sub>7</sub>	Åkermanite
III. Cyclosilicates	Rings	2	12	BaTiSi <sub>3</sub> O <sub>9</sub>	Benitoite
IV. Inosilicates	Chains	2	12	MgSiO <sub>3</sub>	Enstatite
V. Phyllosilicates	Sheets	3	10	Mg <sub>3</sub> (OH) <sub>2</sub> Si <sub>4</sub> O <sub>10</sub>	Talc
VI. Tectosilicates	Frameworks	4	8	SiO <sub>2</sub>	Quartz

One other complication is important: in the SiO<sub>4</sub> tetrahedrons of silicates, some of the silicon atoms may be replaced by aluminum (or occasionally beryllium or boron) atoms. Of course this changes the electric charge of the tetrahedrons. For example, SiO<sub>2</sub>, as such, has zero charge; for convenience it may be written as Si<sub>12</sub>O<sub>24</sub>; if one-quarter of the Si atoms are replaced by Al atoms, the formula becomes Si<sub>9</sub>Al<sub>3</sub>O<sub>24</sub>, which is no longer neutral—it has a charge of  $-3$ ; if this is satisfied by K ions the formula is K<sub>3</sub>Si<sub>9</sub>Al<sub>3</sub>O<sub>24</sub>, or, as usually written, KAlSi<sub>3</sub>O<sub>8</sub>, which is orthoclase. If one-third of the Si atoms are replaced by Al atoms, the formula becomes Si<sub>8</sub>Al<sub>4</sub>O<sub>24</sub>, with a charge of  $-4$ ; if this is satisfied by K ions the formula is K<sub>4</sub>Si<sub>8</sub>Al<sub>4</sub>O<sub>24</sub>, or KAlSi<sub>2</sub>O<sub>6</sub>, which is leucite. If half the Si atoms are replaced by Al atoms, the formula becomes Si<sub>6</sub>Al<sub>6</sub>O<sub>24</sub>, with a charge of  $-6$ ; if this charge is satisfied by Na ions the formula is Na<sub>6</sub>Si<sub>6</sub>Al<sub>6</sub>O<sub>24</sub>, or NaAlSiO<sub>4</sub>, which is nephelite. Thus the three-dimensional framework illustrated by quartz may become the basis of structures which might be classed by their chemical formulas in various cases with phyllosilicates or inosilicates or nesosilicates. Al atoms can proxy for Si atoms not only in the three-dimensional frameworks but in many other silicate structures.

As already mentioned, some minerals have their silica tetrahedrons linked to their neighbors in more than one way. Thus a single crystal structure may illustrate two of the preceding cases. For example, vesuvianite contains single tetrahedrons (SiO<sub>4</sub>) and also pairs of tetrahedrons (Si<sub>2</sub>O<sub>7</sub>) in different parts of the same structure. To show this, the formula may be written: Ca<sub>10</sub>Al<sub>4</sub> $\left\{ \begin{matrix} (\text{SiO}_4)_5 \\ (\text{Si}_2\text{O}_7)_2 \end{matrix} \right\} 2\text{Mg}(\text{OH})_2$ . Therefore it could be included in the nesosilicates or the sorosilicates. Amphibole has half its tetrahedrons linked to two others and half linked to three

<sup>2</sup> The names of the classes are those proposed by H. Strunz (*Mineral. Tabellen*, 1941) and M. Fleischer (1947 Preprint 117, A.S.T.M.). The prefixes mean: *neso*, island; *soro*, group; *cyclo*, ring; *ino*, thread (or chain), *phyllo*, sheet; *tecto*, framework.

others (see Fig. 132); this can be shown in a generalized formula as  $R_7 \left\{ \begin{smallmatrix} \text{Si}_2\text{O}_6 \\ \text{Si}_2\text{O}_5 \end{smallmatrix} \right\} (\text{OH})_2$ , which becomes  $(\text{Mg,Fe})_7\text{Si}_4\text{O}_{11}(\text{OH})_2$  for anthophyllite. In zunyite one  $\text{SiO}_4$  tetrahedron shares all its oxygen atoms with four surrounding  $\text{SiO}_4$  tetrahedrons, but these each share only one oxygen atom with another tetrahedron; the formula can be written:  $R_m \left\{ \begin{smallmatrix} \text{SiO}_2 \\ (\text{Si}_2\text{O}_7)_2 \end{smallmatrix} \right\}$  or  $R_m\text{Si}_5\text{O}_{16}$  or  $\text{Al}_{13}\text{O}_4(\text{OH,F})_{18}\text{ClSi}_5\text{O}_{16}$ . In a few minerals Be, like Al, may replace Si in the tetrahedrons; accordingly beryl may be considered to have a three-dimensional framework with

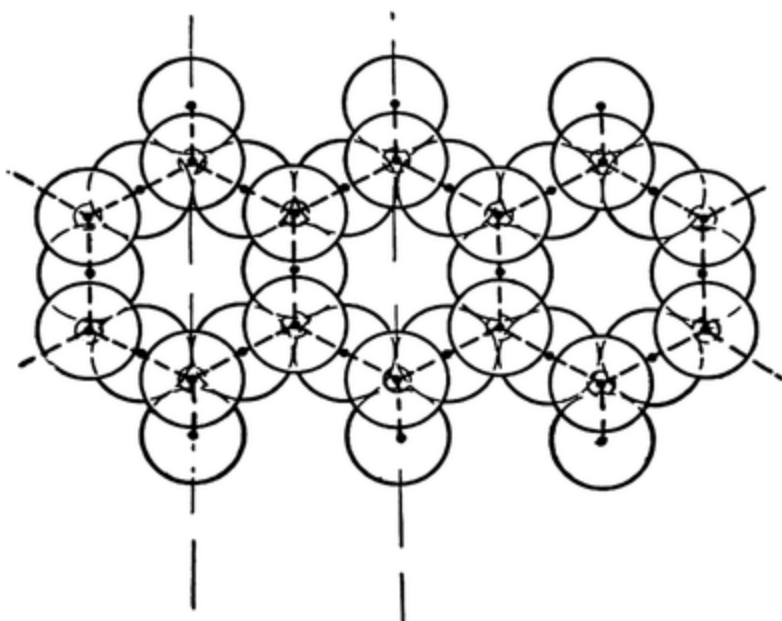


FIG. 132.  $\text{SiO}_4$  groups forming a double continuous chain or band  $(\text{Si}_4\text{O}_{11})_n$ .

the formula  $\text{Al}_2(\text{Si}_6\text{Be}_3)\text{O}_{18}$ , though it clearly has hexagonal  $\text{Si}_6\text{O}_{18}$  rings also; it is a cyclosilicate only if the  $\text{BeO}_4$  tetrahedrons are considered as unlike the  $\text{SiO}_4$  groups.

Silicates which have their  $\text{SiO}_4$  tetrahedrons grouped in layers (and formulas including  $\text{Si}_2\text{O}_5$  or a multiple) have other elements also in parallel layers. Some minerals containing no silica have structures characterized by similar sheets, as illustrated by brucite. The number of such layers in the unit cell is constant in one phase of one compound<sup>3</sup> but varies greatly in different minerals as illustrated in the following examples. As in other silicates, the silicon atoms in the  $\text{SiO}_4$  tetrahedrons may be replaced in part by aluminum atoms.

<sup>3</sup> But different types of moissanite have 15, 21, 33, 51, and 87 layers! See L. S. Ramsdell: *Am. Mineral.*, XXXII, 64 (1947).

## FIVE PLANES OF ATOMS

Plane Number	Coordination with O + OH Ions	Kaolinite <sup>4</sup>	
		Ions	Spacing (Å)
1		O <sub>6</sub>	0.60
2	Tetrahedral	Si <sub>4</sub>	1.59
3		O <sub>4</sub> (OH) <sub>2</sub>	1.06
4	Octahedral	Al <sub>4</sub>	1.06
5		(OH) <sub>6</sub>	3.06
1		O <sub>6</sub>	

## FOURTEEN PLANES OF ATOMS

Plane Number	Coordination with O + OH Ions		
		Talc <sup>5</sup>	Pyrophyllite
1		O <sub>6</sub>	O <sub>6</sub>
2	Tetrahedral	Si <sub>4</sub>	Si <sub>4</sub>
3		O <sub>4</sub> (OH) <sub>2</sub>	O <sub>4</sub> (OH) <sub>2</sub>
4	Octahedral	Mg <sub>6</sub>	Al <sub>4</sub>
5		O <sub>4</sub> (OH) <sub>2</sub>	O <sub>4</sub> (OH) <sub>2</sub>
6	Tetrahedral	Si <sub>4</sub>	Si <sub>4</sub>
7		O <sub>6</sub>	O <sub>6</sub>
8		O <sub>6</sub>	O <sub>6</sub>
9	Tetrahedral	Si <sub>4</sub>	Si <sub>4</sub>
10		O <sub>4</sub> (OH) <sub>2</sub>	O <sub>4</sub> (OH) <sub>2</sub>
11	Octahedral	Mg <sub>6</sub>	Al <sub>4</sub>
12		O <sub>4</sub> (OH) <sub>2</sub>	O <sub>4</sub> (OH) <sub>2</sub>
13	Tetrahedral	Si <sub>4</sub>	Si <sub>4</sub>
14		O <sub>6</sub>	O <sub>6</sub>
1		O <sub>6</sub>	O <sub>6</sub>

It is readily seen that the first layer consisting of seven planes is chemically exactly repeated in the second layer; however, all fourteen planes are required in the unit cell because the second layer is displaced (in the plane 001) with respect to the first layer. It is also easy to see why these minerals have remarkably good basal cleavage—it is because of the lack of any ionic (*i.e.*, electric) attraction between planes 7 and 8

<sup>4</sup> G. W. Brindley and K. Robinson: *Nature*, CLVI, 661 (1945); *Mineral. Mag.*, XXVII, 242 (1946).

<sup>5</sup> A. Brammell, J. G. C. Leech, and F. A. Bannister: *Mineral. Mag.*, XXIV, 507 (1937).

and also between planes 14 and 1 and the consequently wide spacing between these planes.

## SIXTEEN PLANES OF ATOMS

(First half shown)

Plane Number	Coordination with O Ions	Muscovite <sup>5</sup>		Biotite		Margarite
		Ions	Spacing (Å)	Phlogopite <sup>5</sup> (Annite)	Eastonite (Siderophyllite)	
1	Dodecahedral	K <sub>2</sub>	1.68	K <sub>2</sub>	K <sub>2</sub>	Ca <sub>2</sub>
2		O <sub>6</sub>	0.59	O <sub>6</sub>	O <sub>6</sub>	O <sub>6</sub>
3	Tetrahedral	AlSi <sub>3</sub>	1.60	AlSi <sub>3</sub>	AlSi <sub>3</sub>	Al <sub>2</sub> Si <sub>2</sub>
4		O <sub>4</sub> (OH) <sub>2</sub>	1.10	O <sub>4</sub> (OH) <sub>2</sub>	O <sub>4</sub> (OH) <sub>2</sub>	O <sub>4</sub> (OH) <sub>2</sub>
5	Octahedral	Al <sub>4</sub>	1.10	{Mg <sub>6</sub> (Fe <sub>6</sub> )}	{Mg <sub>6</sub> Al (Fe <sub>6</sub> Al)}	Al <sub>4</sub>
6		O <sub>4</sub> (OH) <sub>2</sub>	1.60	O <sub>4</sub> (OH) <sub>2</sub>	O <sub>4</sub> (OH) <sub>2</sub>	O <sub>4</sub> (OH) <sub>2</sub>
7	Tetrahedral	AlSi <sub>3</sub>	0.59	AlSi <sub>3</sub>	Al <sub>2</sub> Si <sub>2</sub>	Al <sub>2</sub> Si <sub>2</sub>
8		O <sub>6</sub>	1.68	O <sub>6</sub>	O <sub>6</sub>	O <sub>6</sub>

Monoclinic domatic mica <sup>6</sup> has only one layer (of eight planes) or else six layers; monoclinic prismatic mica has two layers, as shown above; trigonal trapezohedral mica has three layers; triclinic pinacoidal mica has six layers or even twenty-four layers.

TWENTY PLANES OF ATOMS <sup>6</sup>

(First half shown)

Plane Number	Coordination with O Ions	Dickite	Chlorite	Cookeite
1		O <sub>6</sub>	O <sub>6</sub>	O <sub>6</sub>
2	Tetrahedral	Si <sub>4</sub>	AlSi <sub>3</sub>	AlSi <sub>3</sub>
3		O <sub>4</sub> (OH) <sub>2</sub>	O <sub>4</sub> (OH) <sub>2</sub>	O <sub>4</sub> (OH) <sub>2</sub>
4	Octahedral	Al <sub>4</sub>	Mg <sub>6</sub>	Al <sub>4</sub>
5		(OH) <sub>6</sub>	O <sub>4</sub> (OH) <sub>2</sub>	O <sub>4</sub> (OH) <sub>2</sub>
6	Si Tetrahedral	O <sub>6</sub>	AlSi <sub>3</sub>	AlSi <sub>3</sub>
7	Si Tetrahedral	Si <sub>4</sub>	O <sub>6</sub>	O <sub>6</sub>
8		O <sub>4</sub> (OH) <sub>2</sub>	(OH) <sub>6</sub>	(OH) <sub>6</sub>
9	Octahedral	Al <sub>4</sub>	Mg <sub>4</sub> Al <sub>2</sub>	Li <sub>2</sub> Al <sub>4</sub>
10		(OH) <sub>6</sub>	(OH) <sub>6</sub>	(OH) <sub>6</sub>

An outline of the classification of the silicates follows:

<sup>6</sup> S. B. Hendricks: *Am. Mineral.*, XXIV, 729 (1939).



- A. Tectosilicates (frameworks of tetrahedrons). Type formula  $A_m(BX_2)_n$ .
1. With  $m = \text{zero}$  (silica).
  2. With  $m > \text{zero}$ .
    - (a) Without additional anions  $\begin{cases} \text{Anhydrous (feldspars, etc.).} \\ \text{Hydrous (zeolites).} \end{cases}$
    - (b) With additional anions.
- B. Phyllosilicates (sheets of tetrahedrons).
1. Type formula  $A_m(B_2X_5)_n$ .
    - (a) Without additional anions  $\begin{cases} \text{Anhydrous.} \\ \text{Hydrous.} \end{cases}$
    - (b) With additional anions  $\begin{cases} \text{Anhydrous (micas, chlorite, etc.).} \\ \text{Hydrous.} \end{cases}$
- C. Inosilicates (chains of tetrahedrons).
1. Type formula  $A_m(BX_3)_n$  chain  $\begin{cases} \text{Anhydrous (pyroxenes, etc.).} \\ \text{Hydrous.} \end{cases}$
  2. Type formula  $A_m(B_4X_{11})_n$  double chain  $\begin{cases} \text{Anhydrous (amphiboles).} \\ \text{Hydrous.} \end{cases}$
  3. Type formula  $A_mB_3X_7$  triple chain (Eudidymite).
  4. Type formula  $A_mB_4X_9$  quadruple chain (Epidote).
- D. Cyclosilicates (rings of tetrahedrons).
1. Trigonal rings. Type formula  $A_m(B_3X_9)_n$ .
  2. Tetragonal rings. Type formula  $A_m(B_4X_{12})_n$ .
  3. Hexagonal rings. Type formula  $A_m(B_6X_{18})_n$ .
- E. Sorosilicates (groups of two or more  $\text{SiO}_4$  tetrahedrons).
1. Type formula  $A_m(B_2X_7)_n$ .
    - (a) Without additional anions.
    - (b) With additional anions.
  2. Type formula  $A_m(B_5X_{16})_n$ .
- F. Nesosilicates (single  $\text{SiO}_4$  tetrahedrons).
1. Type formula  $A_m(BX_4)_n$ .
    - (a) Without additional anions  $\begin{cases} \text{Anhydrous.} \\ \text{Hydrous.} \end{cases}$
    - (b) With additional anions (not O)  $\begin{cases} \text{Anhydrous.} \\ \text{Hydrous.} \end{cases}$
    - (c) With additional O anions ("Subsilicates")  $\begin{cases} \text{Anhydrous.} \\ \text{Hydrous.} \end{cases}$

## A. TECTOSILICATES (FRAMEWORKS OF TETRAHEDRONS) WITH TYPE FORMULA $A_m(BX_2)_n$

### 1. With $m = \text{zero}$ (silica)

Of course silica is an oxide ( $\text{SiO}_2$ ), but it may also be considered to be a silicate of silicon; it is so classified here because its crystal structure is closely related to those of many silicates. Silica has many crystal phases, which may be briefly described as follows:

Quartz is the stable phase below  $870^{\circ}$ ; it is metastable above that temperature.  $\alpha$ -Quartz is stable below  $572^{\circ}$  and has trigonal trapezohedral symmetry; on heating it inverts promptly at  $572^{\circ}$  to  $\beta$ -quartz which is stable between  $572^{\circ}$  and  $870^{\circ}$  and has hexagonal trapezohedral symmetry.

$\alpha$ -Tridymite is the stable phase between  $870^{\circ}$  and  $1470^{\circ}$ ; it is metastable below  $870^{\circ}$  and also above  $1470^{\circ}$ , fusing at about  $1625^{\circ}$ ; it is orthorhombic in symmetry.  $\alpha$ -Tridymite may invert to  $\beta_1$ -tridymite at  $117^{\circ}$  or to  $\beta_2$ -tridymite at  $163^{\circ}$ ; both are hexagonal (though different) in symmetry.

Cristobalite is the stable phase from  $1470^{\circ}$  to the melting point at  $1710^{\circ}$ . It is metastable below  $1470^{\circ}$ , tending to invert from the isometric  $\alpha$ -phase to the orthorhombic  $\beta$ -phase at  $200$ – $275^{\circ}$ .

Quartz, tridymite, and cristobalite are all found in nature at ordinary temperature.

**QUARTZ**      **HEXAGONAL (TRIGONAL TRAPEZOHEDRAL)**      **SiO<sub>2</sub>**  
 $c/a = 1.09997$

COMP. Quartz is extraordinarily simple and constant in composition.

STRUC. Space group <sup>7</sup>  $C3_12$  or  $C3_22$ ;  $a$  4.903,  $c$  5.393 Å. U.C. 3.

PHYS. CHAR. Crystals usually prismatic,  $\{10\bar{1}0\}$ , terminated by two rhombohedrons,  $\{10\bar{1}1\}$  and  $\{01\bar{1}1\}$ . Sometimes in double six-sided pyramids made up of the two rhombohedrons. Crystals also highly modified, and malformed. Horizontal striations common on prism faces. Often massive, from coarse to fine granular or even (rarely) to cryptocrystalline and isotropic.<sup>8</sup> Twinning common (though rarely seen in thin section); twinning axis is  $c$  in Dauphiné twins; twinning plane is  $11\bar{2}0$  in Brazil twins which have no twinning axis; other types of twinning are known. Cleavage<sup>9</sup> absent or difficult and poor parallel to  $10\bar{1}1$ , etc. Fracture conchoidal. H. = 7. G. = 2.65. F. = 7. Insoluble in acids except HF. Has pyroelectric and piezoelectric properties.

OPT. PROP. Uniaxial positive with low relief and weak birefringence. Rotary polarization (invisible in thin sections) increasing with the thickness of the section. Right-handed and left-handed crystals about equally common; the combination of these two produces Airy spirals.

On account of the extraordinarily constant composition (pure SiO<sub>2</sub>) the indices of refraction vary only in the fifth or sixth decimal place; averaging reliable measures the values are:

<sup>7</sup> R. W. G. Wyckoff: *Am. Jour. Sci.*, CCXI, 101 (1926).

<sup>8</sup> A. N. Winchell: *Am. Mineral.*, IX, 235 (1924).

<sup>9</sup>  $\beta$ -Quartz has distinct  $10\bar{1}1$  and  $10\bar{1}0$  cleavages.

$\lambda = 6872(B)$	6708(Li)	6563(C)	5893(D)	5350(Tl)	4861(F)	F - C
$N_E = 1.5504$	1.55048	1.55093	1.55336	1.55600	1.55898	0.00805
$N_O = 1.5514$	1.54147	1.54190	1.54425	1.54680	1.54968	0.00778
$N_E - N_O = 0.0090$	0.00901	0.00903	0.00911	0.00920	0.00930	0.00027

The refringence decreases very slowly with rise of temperature (about 7 per degree in the sixth decimal place). The birefringence also decreases slowly (to  $570^\circ$ ). Since the index for the ordinary ray does not vary with the orientation, the index  $N_O = 1.54425$  (the index in white light is nearly the same as in sodium light) is constant in all sections and is useful for exact comparisons.

Quartz in some crystals shows a distinctly biaxial character (due to strain?);  $2E$  may be  $12^\circ$ – $18^\circ$ , or even as much as  $24^\circ$ .

Quartz is colorless in thin sections but often shows inclusions of various kinds which serve as pigments and give color to thick sections and masses of the mineral. Thus quartz may be yellow, red, brown, green, blue, black. Streak colorless. Luster vitreous.

INCL. Liquid inclusions are especially common in quartz. The liquid may be water, or  $CO_2$ , or both. Gaseous bubbles, sometimes movable, often accompany the liquid inclusions. These inclusions occupy cavities which, rarely, may have the form of the enclosing quartz; such cavities are called negative crystals. Cubes, probably of  $NaCl$ , are sometimes found in such cavities. Occasionally, the liquid present is a carbide and causes the fetid odor of certain pieces of quartz when struck a sharp blow.

The inclusions in quartz may be irregular in distribution or arranged along curved lines or surfaces, or they may be parallel to certain crystal faces. Only rarely are they quite large and easily visible without a lens. The solid inclusions in quartz may be reticulated rutile (*Venus' hair*), needles of tourmaline, epidote, actinolite (when regularly arranged so as to produce opalescence these make the variety of quartz called *cat's-eye*), chlorite, or other lamellar minerals. Quartz containing reticulated rutile or other acicular mineral is often called *sagenite*.

INVER. Upon heating, quartz changes from the  $\alpha$ - to the  $\beta$ -phase promptly at  $573^\circ$ , and the change reverses on cooling just as promptly. The change involves a 2 per cent change of volume.  $\beta$ -Quartz is hexagonal trapezohedral and has good  $10\bar{1}1$  and  $10\bar{1}0$  cleavages. At  $580^\circ$  it has  $(+ )2V = 0^\circ$ ,  $N_O = 1.5329(D)$ ,  $N_E = 1.5405$ ,  $N_E - N_O = 0.0066$ . The rotatory power of  $\beta$ -quartz at  $573^\circ$  is measurably greater than that of  $\alpha$ -quartz at  $573^\circ$ . Space group  $C6_22$  or  $C6_42$ ;  $a$  5.01,  $c$  5.47 Å. U.C. 3. Quartz which was formed at temperatures above  $573^\circ$  and has inverted on cooling can usually be distinguished from quartz which has

never been as hot as  $573^{\circ}$  by the following features:<sup>10</sup> (1) Crystal form. The presence of the trigonal trapezohedron is evidence of the low-temperature phase. See Fig. 133. Simple pyramidal, rather than prismatic rhombohedral, habit is an indication of  $\beta$ -quartz. See Fig. 134. (2) Character of twinning, especially as shown by etch figures on the basal pinacoid. In  $\alpha$ -quartz the twinning is simple and regular; in quartz which was once the  $\beta$ -phase and has inverted, it is irregular in small patches bearing no relation to the external form. (3) Intergrowths of right- and left-handed quartz are more frequent and more regular in  $\alpha$ -quartz. (4) Inversion produces some shattering, due to a distinct change of volume.

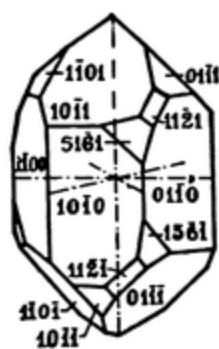


FIG. 133. A crystal habit of low-temperature quartz.

Quartz undergoes a second inversion at  $870^{\circ}$  to tridymite, and tridymite inverts at  $1470^{\circ}$  to cristobalite, but these changes are very sluggish and occur only under especially favorable conditions. The reverse changes, on cooling, are also possible, but very sluggish.

**ALTER.** Quartz is a very stable mineral; in rare cases it is replaced by talc, pyrite, cassiterite, magnetite, or some other mineral. Inversely, quartz is found in pseudomorphs after many minerals, notably calcite, fluorite, barite, etc. When fused in nature "embayments" may first be formed before the whole mass is fused. In acid rocks fused quartz recrystallizes at high temperatures as tridymite (or cristobalite).

**OCCUR.** Quartz is one of the most abundant minerals found in nature; it is an essential constituent of rhyolite, granite, dacite, tonalite, gneiss, micaschist, and many related rocks. It is usually the chief, and often nearly the only, constituent of sandstone, quartzite, gravel, conglomerate, and vein rocks. It occurs in less important amounts in many other igneous, metamorphic, and sedimentary rocks. It is often deposited by hot springs and geysers.

**DIAG.** The low refringence, weak birefringence, and absence of visible twinning, color, cleavage, or alteration usually serve to identify quartz. It may be distinguished from colorless cordierite by its uniaxial character and lack of twinning. Other characters of note include the specific gravity, hardness, crystal form, and resistance to acids, except HF.

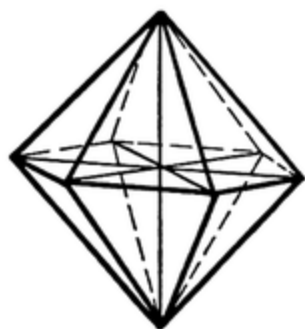


FIG. 134. A crystal habit of high-temperature quartz.

<sup>10</sup> As given by F. E. Wright and E. S. Larsen: *Am. Jour. Sci.*, CLXXVII, 438 (1909).

*Chalcedony* is a fibrous variety of quartz, containing opal and other impurities, and (doubtless) submicroscopic cavities.  $H. = 6$ .  $G. = 2.55-2.63$ .  $F. = 7$ . Uniaxial with  $N_O$  reported as 1.533-1.539,  $N_E$  as 1.530; the indices vary and differ from those of quartz probably because of impurities and form birefringence.<sup>11</sup> Some chalcedony seems to have fibers elongated along  $c$ , some normal to  $c$ , and some at about  $30^\circ$  to  $c$ . The first two give parallel extinction and the third extinction at about  $30^\circ$  (*lutécite*). The first gives positive elongation (*quartzine*), the second negative elongation, and a combination of these two gives  $\pm$  elongation. Many varieties of chalcedony are recognized, depending upon color, structure, etc.: such as *carnelian*, *sard*, *prase*, *agate*, *onyx*, *sardonyx*, *jasper*, and *bloodstone*. Chalcedony is often spherulitic, mammillary, botryoidal, or stalactitic. Color white, gray, brown, red, black, green, etc.

**TRIDYMITE**

ORTHORHOMBIC (PSEUDOHEXAGONAL)

 $SiO_2$ 

**COMP.** Usually considered very pure  $SiO_2$ , like quartz, but the properties vary and Lukesh<sup>12</sup> found impurities enough to give the empirical formula  $NaCaAl_3Si_{15}O_{36}$ . Barth found 5.2 per cent  $NaAlSiO_4$  in crystal solution.

**STRUC.** Space group<sup>12</sup>  $Fmm$ ,  $Fmmm$ , or  $F222$ ;  $a$  9.88,  $b$  17.1,  $c$  16.3 Å. U.C. 64.<sup>13</sup>

**PHYS. CHAR.** Crystals usually six-sided basal plates; often in random aggregates of minute units with wedge-like twinning. Basal plates show twinning on 110 in sectors as in aragonite and cordierite, the optic plane being normal to the external boundary. Occasional pseudo-isometric forms are probably due to inversion from cristobalite. Indistinct prismatic cleavage and basal parting.  $H. = 7$ .  $G. = 2.27$ .  $F. = 7$ . Soluble in boiling  $Na_2CO_3$ .

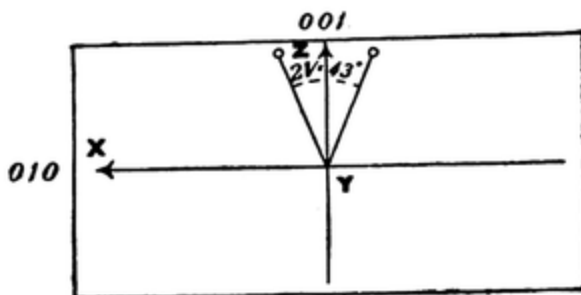


FIG. 135. The optic orientation of tridymite.

**OPT. PROP.** The optic plane is 100;

$Z = c$ . See Fig. 135. The relief is negative and the birefringence weak. Measures of properties show considerable variations (due to variations in composition?<sup>12</sup>) as follows:

(+)2V	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$	Author
$76^\circ 15'$	1.471	1.472	1.474	0.003	Heide <sup>14</sup>
?		1.469-1.479			Kondo <sup>15</sup>
$66^\circ-90^\circ$	1.478	1.479	1.481	0.0025	Durrell <sup>16</sup>
?	1.479	1.480	1.483	0.004	Barth <sup>17</sup>

The optic angle is small in some samples; for example,  $2V = 35^\circ$  ca.

<sup>11</sup> J. D. H. Donnay: *Ann. Soc. géol. Belg.*, LIX, B289 (1936).

<sup>12</sup> J. Lukesh: *Am. Mineral.*, XXVII, 143 (1942). Lukesh gives  $c = 81.75$  Å!  
See also M. J. Buerger: *Zeit. Krist.*, XC, 186 (1935).

<sup>13</sup> R. E. Gibbs: *Proc. Roy. Soc.*, A, CXIII, 351 (1926).

<sup>14</sup> F. Heide: *Cent. Mineral.*, 1923, 69.

<sup>15</sup> S. Kondo and T. Yamauchi: *Jour. Soc. Chem. Ind. Japan*, XXXVIII, Sup. 651 (1935).

<sup>16</sup> C. Durrell: *Am. Mineral.*, XXV, 501 (1940).

<sup>17</sup> T. F. W. Barth and A. Kvalheim: *Norsk. Vidensk. Akad. Oslo*, XXII, 1 (1944).



Colorless or white; colorless in thin section.

INCL. Gas inclusions are not rare.

INVER. Tridymite is the stable form of  $\text{SiO}_2$  between  $873^\circ$  and  $1470^\circ$ ; inversion to quartz (below  $873^\circ$ ) and to cristobalite (above  $1470^\circ$ ) is very sluggish, so that tridymite is found in nature at ordinary temperature, and has been heated till fused at about  $1625^\circ$ . Low-temperature  $\alpha$ -tridymite inverts to  $\beta_1$ -tridymite at  $117^\circ$  and to  $\beta_2$ -tridymite at  $163^\circ$ . The former <sup>13</sup> is hexagonal with  $c/a = 1.634$ ; the latter is also uniaxial and hexagonal, the change at  $163^\circ$  being perhaps from hemihedral to holohedral symmetry. On cooling the reversions show some lag. With 5.2 per cent nepheline in crystal solution Barth <sup>17</sup> found a single inversion at  $135^\circ \pm 5^\circ$ .

OCCUR. Tridymite is found usually in aggregates of basal plates in lithophysae; it is also known in meteorites.

DIAG. Tridymite differs from cristobalite in its slightly higher refractive index, its lamellar shape with negative elongation and parallel extinction, and its wedge-shaped twins. Also, the inversion temperatures are characteristic.

### CRISTOBALITE TETRAGONAL? <sup>18</sup> (PSEUDO-ISOMETRIC) $c/a = 1.395$ $\text{SiO}_2$

COMP. Usually considered very pure  $\text{SiO}_2$  like quartz, but Buerger <sup>12</sup> finds that it often contains other elements, Al, Fe, Na, Ca, etc. *Melanophlogite* ( $\text{SiO}_2$  with a little  $\text{SO}_3$  or  $\text{SiS}_2$ ) is doubtless a variety. It is colorless or yellow and turns black on heating.  $G. = 2.04$ .  $N = 1.461(-1.45)$ .

STRUC. Space group <sup>19</sup>  $P4_12_1$ ;  $a$  7.02,  $c$  6.92 Å. U.C. 8.

PHYS. CHAR. Crystals pseudo-octahedral or skeletal; twinning on 111.  $H. = 6-7$ .  $G. = 2.33$ .  $F. = 1710^\circ$ . Insoluble except in HF.

OPT. PROP. Uniaxial negative with negative relief and very weak birefringence. Some parts may be biaxial.  $N_O = 1.487$ ,  $N_E = 1.484$ ,  $N_O - N_E = 0.003$ .

Colorless in section. Milky white in mass. Luster vitreous.

*Lussatite* and *lussatine* <sup>20</sup> are fibrous cristobalite; the fibers of lussatite have positive elongation, and those of lussatine have negative elongation.

INVER. Low temperature  $\alpha$ -cristobalite inverts on heating to  $\beta$ -cristobalite at  $198^\circ-240^\circ \text{C.}$  with a 2.8% decrease of volume.  $\beta$ -cristobalite is isometric tetartoidal <sup>21</sup> with  $a$  7.12 Å and U.C. 8; space group  $P2_13$ ; it has  $N = 1.486$ . On cooling inversion occurs at  $220^\circ-275^\circ \text{C.}$  For a given crystal the inversion is at a fixed temperature, but for other crystals it varies, apparently depending upon previous heat treatment. Cristobalite is the stable form of silica above  $1470^\circ$ ; below that temperature it is metastable but may persist for long periods.

OCCUR. Cristobalite is found in cavities in volcanic rocks. It is easily produced artificially.

DIAG. The crystal form, refractive index, optic sign, and reversible change of state at  $200-275^\circ$  are characteristic. Multiple twinning in bands of one or two intersecting sets is common. Elongated crystals may show extinction at any angle.

**Lechatelierite** ( $\text{SiO}_2$ ) is naturally fused amorphous silica. It is isotropic with  $G. = 2.19$  and  $N = 1.4564 \text{ C, } 1.4584 \text{ D, } 1.4632 \text{ F.}$  Artificially fused quartz has the

<sup>18</sup> T. F. W. Barth (*Am. Jour. Sci.*, CCXXIV, 97, 1932) considers it orthorhombic, but X-ray data indicate tetragonal trapezohedral symmetry.

<sup>19</sup> W. Nieuwenkamp: *Zeit. Krist.*, XCII, 82 (1935); see also A. H. Jay: *Mineral. Mag.*, XXVII, 54 (1944).

<sup>20</sup> F. Laves: *Naturw.*, XXVII, 705 (1939); *Min. Abst.*, VII, 514 (1940).

<sup>21</sup> S. Miller: *Min. Abst.*, X, 64 (1947); see also N. L. Taliaferro: *Am. Jour. Sci.*, CCXXX, 450 (1935).



same index,  $N = 1.4588$ . But ignited silica hydrogel (or chemically precipitated silica) has  $N = 1.48-1.485$ . Lechatelierite is sometimes produced when lightning strikes quartz sand and produces tiny tubes of fused silica (*fulgurites*) in it. It is also known about volcanoes.

*Opal* ( $SiO_2 \cdot nH_2O$ ) is amorphous silica with water (with less than 10%  $H_2O$  it usually contains some cristobalite or quartz). It is capable of absorbing much water and thus becoming more transparent.  $H. = 6$  ca.  $G. = 2.1$  ca.  $F. = 7$ . Soluble in HF and also in KOH. Isotropic, but it may show polarization due to internal strain; globules then show a black cross of negative character like colloidal substances, *e.g.*, gelatin, which contract on solidifying. Refrindex varies with the tenor of water.

$H_2O = 3.5\%$	6.33	8.97	28.04 (Artificial)
$N = 1.4592$	1.4531	1.4465	1.409
$G. = 2.16$	2.096	2.036	1.731

Opal is colorless, white, milky, yellow, brown, red, green, blue, or black. Precious opal shows a play of colors. Colorless in thin section.

Inclusions of various kinds are common. Opal may change to a crystalline state, but it then loses water. It is found in rocks of all kinds, but is always secondary in origin. It may be formed by the alteration of silicates in igneous or sedimentary rocks; it may be deposited from solution about geysers or in veins or cavities; it may be of organic origin; or it may be concretionary in sedimentary rocks. The distinctive characters of opal are the distinct negative relief, the isotropic condition, the mode of formation, the colloidal structure, the low specific gravity, and the solubility in alkalis as well as in HF.

## 2. With $m > \text{zero}$

### (a) WITHOUT ADDITIONAL ANIONS—ANHYDROUS (FELDSPARS, ETC.)

#### LEUCITE



PSEUDO-ISOMETRIC (TETRAGONAL TRAPEZOHEDRAL)<sup>22</sup>

COMP. Often contains a little  $NaAlSi_2O_6$ ; still less  $CaO$ , etc.

STRUC. Space group  $I4_12?$ ;  $a$  12.95,  $c$  13.65 Å;  $c/a = 1.054$ . U.C. 16.

PHYS. CHAR. Crystals usually trapezohedral (Fig. 136), often with {100} or {110}. Very poor 110 cleavage.  $H. = 5.5-6$ .  $G. = 2.47$ . Fuses at 1686°. Decomposed by HCl.

OPT. PROP. Small crystals usually isotropic; large crystals usually weakly anisotropic, the isometric structure being unstable or metastable

<sup>22</sup> J. Wyart: *C. R. Acad. Sci. Paris*, CCIII, 938 (1936). But F. A. Bannister (*Mineral. Mag.*, XXII, 469, 1931) considered it orthorhombic, and E. Onorato (*Min. Abst.*, VII, 237, 1939) considered it monoclinic on X-ray evidence, and optically orthorhombic!

<sup>23</sup> Whenever Al (or Be or B) follows Si in a formula it means that this atom is in tetrahedral coordination and proxies for a Si atom.

below about  $600^{\circ}$ ; the external isometric form is maintained by means of complicated twinning on 110 of the tetragonal(?) unit. See Fig. 137.  $(+ )2V =$  very small,  $N_O = 1.508$ ,  $N_E = 1.509$ ,  $N_E - N_O = 0.001$  ( $N = 1.5054$  B,  $1.5146$  F). The weakly birefringent twinning bands are seen more easily by superposing a sensitive tint plate.



FIG. 136. A crystal form of leucite.

Colorless, white, or gray. Colorless in thin section.

**INVER.** The inversion temperature to the isometric hexoctahedral form seems to vary between  $500^{\circ}$  and  $700^{\circ}$ . A temperature-inversion interval of about  $30^{\circ}$  has been suggested. The isometric phase <sup>24</sup> belongs to space group  $Ia3d$  and has  $a$  13.40 Å.

**INCL.** Inclusions of glass, magnetite, etc., are common (see Fig. 138); they may be regularly arranged either radially or parallel to the faces of the leucite crystals. Various stages in the development of radial inclusions through growth of skeleton crystals are shown in Fig. 139.

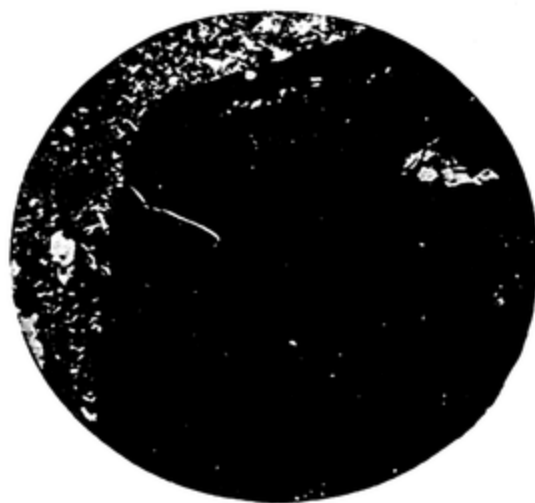


FIG. 137. Photomicrograph of leucite in thin section showing its very weak birefringence.

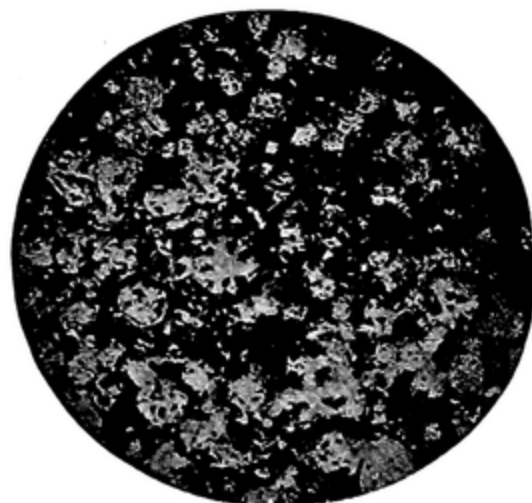


FIG. 138. Photomicrograph of leucite crystals in thin section showing imperfectly arranged radial inclusions.

**ALTER.** Leucite alters easily, either to analcite, as in Tertiary and Recent lavas, or to the so-called *pseudoleucite* (as in Paleozoic rocks), which is an aggregate of albite and sericite, orthoclase and sericite, or orthoclase and nephelite.

**OCCUR.** Leucite is found only in igneous rocks low in silica and high in potassa. It may occur as part of the groundmass or in phenocrysts.

<sup>24</sup> J. Wyart: *C. R. Acad. Sci. Paris*, CCXII, 356 (1941).

It is largely confined to Tertiary and Recent lavas, because it is almost completely altered in older rocks.

**DIAG.** The low refringence, crystal form, isotropic character or very weak birefringence distinguish leucite from all minerals except analcite; it differs from analcite and sodalite by higher refringence and presence



FIG. 139. Radial inclusions in leucite resulting from the development of a skeletal form. (After Pirsson.)

of potassium; if heated to redness, analcite loses water and becomes opaque, while leucite remains unaltered; sodalite crystals are commonly dodecahedral and fuse at 3.5–4.

**POLLUCITE** DITETRAGONAL DIPYRAMIDAL (PSEUDO-ISOMETRIC)<sup>25</sup>  $CsSi_2AlO_6$

**COMP.** Natural crystals contain 2–5%  $Na_2O$ , about the same tenor of  $H_2O$ , and less  $Rb_2O$ ,  $K_2O$ ,  $Li_2O$ , etc. This leads to a series from  $CsAlSi_2O_6$  to at least 50%  $NaAlSi_2O_6 \cdot H_2O$  (or analcite). See Fig. 140.<sup>26</sup> Pollucite also often contains Si apparently replacing Al and Cs, leading to  $Cs_{14}Al_{14}Si_{34}O_{96}$ .

**STRUC.** Space group<sup>26</sup>  $I4/acd$ ;  $a$  13.71 Å. U.C. 16.

**PHYS. CHAR.** Crystals often cubes. Cleavage only in traces.  $H. = 6.5$ .  $G. = 2.9$ .  $F. = 6$ . Slowly decomposed by HCl.

**OPT. PROP.** Isotropic with<sup>27</sup>  $N = 1.507$ – $1.527$ , decreasing with increase of  $H_2O$  tenor. Dehydration<sup>28</sup> (when heated) lowers the index about 0.01 to 0.015. There

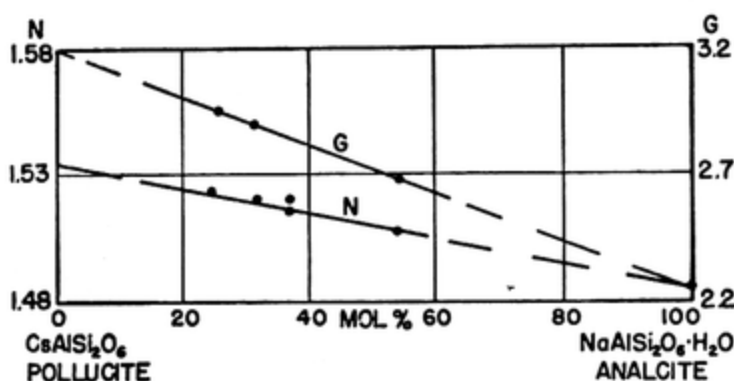


FIG. 140. Properties of the pollucite-analcite (discontinuous?) series.

is a (discontinuous?) series<sup>25</sup> from pollucite to analcite, as shown in Fig. 140. Colorless.

<sup>25</sup> H. Strunz: *Zeit. Krist.*, XCV, 1 (1936). See also Náray-Szabó: *Zeit. Krist.*, XCIX, 277 (1938).

<sup>26</sup> H. J. Nel: *Am. Mineral.*, XXIX, 443 (1944).

<sup>27</sup> Pollucite with  $H_2O$  2.79,  $Na_2O$  3.10,  $Fe_2O_3$  0.32 has  $N = 1.527$ —A.I. Ginsburg: *Chem. Abst.*, XLI, 2664 (1947).

<sup>28</sup> M. Fleischer and C. J. Ksanda: *Am. Mineral.*, XXV, 666 (1940).

**OCCUR.** Found in cavities in granite, and in pegmatite, as on the island of Elba and at Hebron, Maine.

**NEPHELINE** (*Nephelite*) **HEXAGONAL PYRAMIDAL**  $\text{KNa}_3\text{Si}_4\text{Al}_4\text{O}_{16}$   
 $c/a = 0.838$

**COMP.** Natural crystals usually contain 5–20 per cent of  $\text{KAlSiO}_4$  and 3–10 per cent of excess  $\text{SiO}_2$ , probably as  $\text{HAlSiO}_4$ , and sometimes a little  $\text{CaO}$ .  $\text{NaAlSiO}_4$  and  $\text{KAlSiO}_4$  are miscible in all proportions at

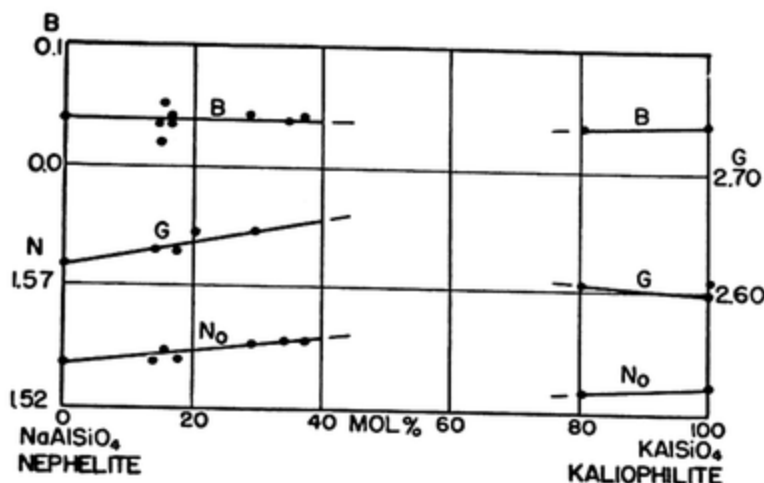


FIG. 141. Properties of the  $\text{NaAlSiO}_4$ - $\text{KAlSiO}_4$  discontinuous series. Based on data of F. A. Bannister and M. H. Hey: *Mineral. Mag.*, XXII, 569 (1931).

high temperature; they form a discontinuous series at low temperature as shown in Fig. 141.

**STRUC.** Space group <sup>29</sup>  $C6_3$ ;  $a$  10.05,  $c$  8.38 Å. U.C. 2. X-ray studies <sup>30</sup> show that the ideal formula is  $\text{KNa}_3\text{Si}_4\text{Al}_4\text{O}_{16}$ .

**PHYS. CHAR.** Crystals often tabular in igneous rocks and prismatic in geodes, with no good cleavage (difficult  $10\bar{1}0$  and  $0001$ ); often massive.  $H. = 5.5-6$ .  $G. = 2.55-2.65$ . The natural mineral fuses at about 4 to colorless glass; pure  $\text{NaAlSiO}_4$  melts at  $1526^\circ$  after inversion at  $1248^\circ$ . Gelatinizes with acids.

**OPT. PROP.** Uniaxial negative; refringence always low and birefringence weak, but both vary appreciably, as follows:

$N_O = 1.536-1.549$ ,  $N_E = 1.532-1.544$ ,  $N_O - N_E = 0.003-0.005$ .

Pure artificial  $\text{NaAlSiO}_4$  has  $N_O = 1.537$ ,  $N_E = 1.533$ ,  $N_O - N_E = 0.004$ , with  $G. = 2.619$  at  $21^\circ$ , according to Bowen,<sup>31,35</sup> but natural

<sup>29</sup> F. A. Bannister and M. H. Hey: *Mineral. Mag.*, XXVI, 218 (1942), give  $a = 9.99$  ca.,  $c = 8.38$  ca. Å.

<sup>30</sup> M. J. Buerger, G. E. Klein, and G. Hamburger: *Am. Mineral.*, XXXII, 197 (1947).

<sup>31</sup> N. L. Bowen: *Am. Jour. Sci.*, CLXXXIII, 49 and 551 (1912); CXCH, 115 (1917).

crystals suggest lower values,<sup>32</sup> and Winkler<sup>33</sup> found  $N_O = 1.532$ ,  $N_E = 1.528$ . Bowen has shown that  $\text{CaAl}_2\text{Si}_2\text{O}_8$  (or  $\text{CaAlAlO}_4$  and  $\text{SiSiO}_4$ ?) in artificial nepheline has no perceptible effect upon  $N_O$ , but increases  $N_E$ , producing an isotropic condition at 23%  $\text{CaAl}_2\text{Si}_2\text{O}_8$ , as shown in Fig. 142. Natural nepheline shows no similar condition; on the contrary, two samples with maximum CaO have about maximum birefringence and a sample with minimum CaO has minimum bire-

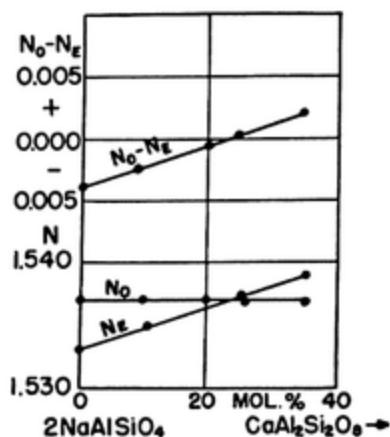


FIG. 142. Properties of the  $2\text{NaAlSiO}_4\text{-CaAl}_2\text{Si}_2\text{O}_8$  partial series. After N. L. Bowen: *Am. Jour. Sci.*, XXXIII, 551 (1912).

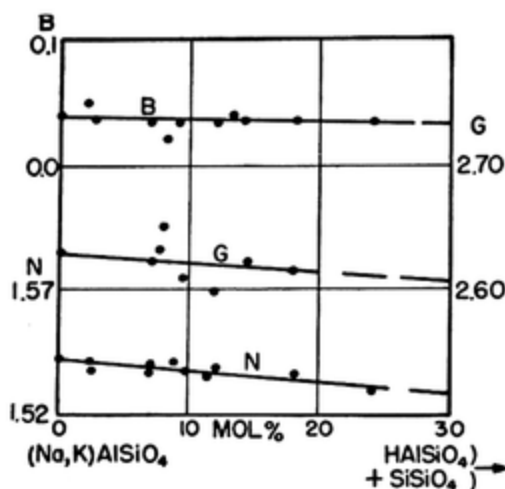


FIG. 143. Properties of the  $(\text{Na},\text{K})\text{AlSiO}_4\text{-HAlSiO}_4 + \text{SiSiO}_4$  partial series.

fringence, although the differences are small.  $\text{HAlSiO}_4$  decreases the indices and density as shown in Fig. 143. The properties of the  $\text{NaAlSiO}_4\text{-KAlSiO}_4\text{-HAlSiO}_4$  system are shown in Fig. 144.

The indices of nepheline may be increased<sup>34</sup> about 0.002 by heating the mineral to  $800^\circ$ .

It is colorless or gray or tinted by impurities. Luster vitreous to greasy. Colorless in thin section.

Pure artificial nepheline inverts at  $1248^\circ$  to an isometric form;<sup>35</sup> on rapid cooling the reverse change does not occur, but the isometric phase changes at about  $690^\circ$  to a metastable triclinic (?) form known as *carnegieite*, which always shows complicated multiple twinning, has  $G. = 2.513$  at  $21^\circ$ , and fuses at  $1526^\circ$ . Carnegieite is biaxial, negative, with  $2V = 12^\circ\text{-}15^\circ$  and  $N_X = 1.509$ ,  $N_Y = 1.514$ ,  $N_Z = 1.514$ ,

<sup>32</sup> F. A. Bannister and M. H. Hey: *Mineral. Mag.*, XXII, 569 (1931).

<sup>33</sup> H. G. F. Winkler: *Am. Mineral.*, XXXII, 131 (1947).

<sup>34</sup> F. Zambonini: *Zeit. Krist.*, LV, 302 (1915).

<sup>35</sup> N. L. Bowen and J. W. Greig: *Am. Jour. Sci.*, CCX, 204 (1925).

$N_Z - N_X = 0.005$ . Colorless. The inversion temperature is higher (at least  $1325^{\circ}$ – $1350^{\circ}$ ) for natural nephelines.

**ALTER.** Nepheline alters in various ways; it may change to a mass of fibrous zeolites (natrolite, sometimes with thomsonite or phillipsite) or to analcite or sodalite; very frequently it alters to cancrinite, this change occurring first along cleavage cracks and fractures and finally

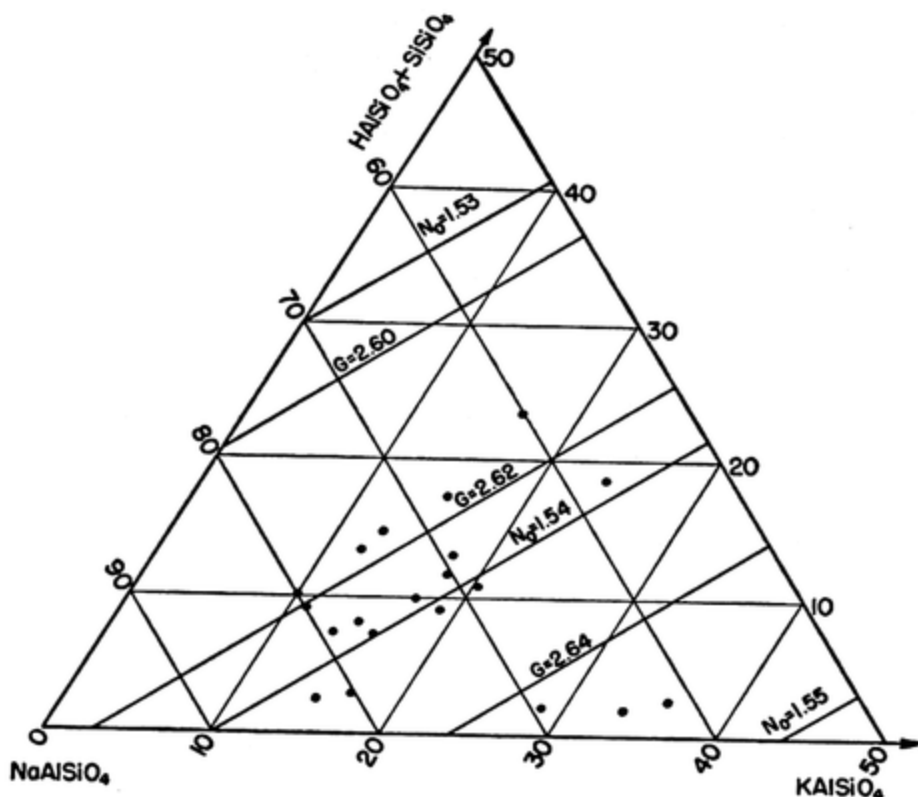


FIG. 144. Properties of the  $\text{NaAlSi}_3\text{O}_4$ - $\text{KAlSi}_3\text{O}_4$ - $\text{HAlSi}_3\text{O}_4 + \text{SiSiO}_4$  partial system.

replacing the whole mass. The cancrinite often has uniform orientation which may be that of the original nepheline. Further, nepheline often changes in a similar way to mica, the laminae commonly being parallel with the basal cleavage of the original mineral. The mica formed is a colorless variety of muscovite which has been called *liebnerite* and also *gieseckite*. Calcite may form at the same time. More rarely nepheline alters to kaolinite, to garnet, or to a colloidal mass.

**OCCUR.** Nepheline is found only in igneous rocks relatively high in soda and low in silica, such as nepheline syenite and phonolite. In such rocks it replaces more or less feldspar.

**DIAG.** Nepheline is distinguished from apatite and melilite by much lower refringence (hence no relief); sodalite is isotropic; scapolite has stronger birefringence and better cleavage; orthoclase is biaxial, has



better cleavage, more twinning, and does not gelatinize with acids. Nepheline has somewhat distinctive alteration products.

**KALIOPHILITE** DIHEXAGONAL DIPYRAMIDAL  $c/a = 0.317$   $KSilAlO_4$

**COMP.**  $KAlSiO_4$  is miscible in all proportions with  $NaAlSiO_4$ , but *only at high temperatures*; at low temperatures the series is quite incomplete—see Fig. 139. Natural kaliophilite contains commonly about 5–20 per cent of  $NaAlSiO_4$ .

**STRUC.** Space group  $^2 C6/mmm$ ;  $a$  27.0,  $c$  8.51 Å. U.C. 54.

**PHYS. CHAR.** Crystals thick prismatic with poor 10 $\bar{1}0$  and 0001 cleavage (or parting?).  $H. = 6$ .  $G. = 2.61$ .  $F. =$  about 1800° (pure  $KAlSiO_4$ ). Gelatinizes with HCl.

**OPT. PROP.** Uniaxial negative with  $N_O = 1.537$ ,  $N_E = 1.533$ ,  $N_O - N_E = 0.004$ . The artificial compound has  $N_O = 1.532$ ,  $N_E = 1.527$ ,  $N_O - N_E = 0.005$ . See Fig. 139. Kaliophilite glass has  $N = 1.508$ . Colorless.

**INVER.** Artificial  $KAlSiO_4$  changes to an orthorhombic phase  $^{36}$  at about 1540°; the latter is metastable at ordinary temperature and has been formed artificially at about 500°. It shows very common twinning often of the aragonite type;  $a$  9.00,  $b$  15.68,  $c$  8.53 Å, and  $G. = 2.60$ . It is biaxial with  $(- )2V = 39^\circ$  and  $N_X = 1.528$ ,  $N_Y = 1.535$ ,  $N_Z = 1.536$ ,  $N_Z - N_X = 0.008$ . Colorless. It has been found in nepheline from West Africa. *Kalsilite*  $^{37}$  seems to be still another phase of  $KAlSiO_4$  (with some Na) very much like nepheline; it is hexagonal trapezohedral with  $c/a = 1.404$  (space group  $C6_32$ ) with  $a$  5.17,  $c$  8.67 Å. U.C. 2.  $G. = 2.59$ . No  $^{38}$  cleavage seen. Uniaxial negative with  $N_O = 1.542$ ,  $N_E = 1.537$ ,  $N_O - N_E = 0.005$ ; again:  $^{38}$   $N_O = 1.537$ ,  $N_E = 1.530$ ,  $N_O - N_E = 0.007$ . Colorless. A microchemical test (described below) is useful to distinguish it (and kaliophilite) from nepheline. It was found in Wales.

**ALTER.** Kaliophilite may change to microsommite, and may be a product of alteration of leucite.

**OCCUR.** Kaliophilite is found only in volcanic rocks rich in potassa and low in silica, as at Monte Somma, Italy.

**DIAG.** Very difficultly distinguishable from nepheline, which is much commoner. A microchemical test may be used. Place a drop of  $N$  HCl on an uncovered thin section or a polished rock surface, and after half a minute add a drop of a strong sodium cobaltinitrite solution; after one or two minutes wash the surface gently.  $KAlSiO_4$ , but not nepheline, will give the yellow stain test for potassium.

**Eucryptite** ( $LiSiAlO_4$ ) is hexagonal with distinct 0001 cleavage.  $G. = 2.67$ . Uniaxial negative with  $N_O = 1.545$ ,  $N_O - N_E =$  weak. Colorless. High temperature  $\alpha$ -eucryptite  $^{39}$  melts at 1388°;  $G. = 2.36$ ; uniaxial negative with  $N_O = 1.527$ – $1.531$ ,  $N_E = 1.521$ – $1.523$ ,  $N_O - N_E = 0.006$ – $0.008$ . Eucryptite is found as an alteration product of spodumene at Branchville, Connecticut.

**Milarite**  $^{40}$  ( $KCa_2Si_{12}Be_2AlO_{30} \cdot 0.5H_2O?$ ) is hexagonal with  $c/a = 1.324$ . Space group  $C6/mcc$ ;  $a$  10.46,  $c$  13.90 Å; U.C. 1. Crystals prismatic without cleavage.  $H. = 5.5$ – $6$ .  $G. = 2.57$ .  $F. =$  easy. Insoluble in acid. Uniaxial (negative) at high

$^{36}$  N. L. Bowen: *Am. Jour. Sci.*, X, 204 (1925).

$^{37}$  F. A. Bannister and M. H. Hey: *Mineral. Mag.*, XXVI, 218 (1942).

$^{38}$  G. R. Rigby and H. M. Richardson: *Mineral. Mag.*, XXVIII, 75 (1947).

$^{39}$  E. Dittler and A. Hofmann: *Chem. Erde*, XI, 256 (1937). R. A. Hatch: *Am. Mineral.*, XXVIII, 471 (1943).

$^{40}$  C. Palache: *Am. Mineral.*, XVI, 469 (1931).

temperature; biaxial with small  $2V$  at ordinary temperature, basal sections showing six radial segments with a central part which may be uniaxial.  $N_O = 1.532$ ,  $N_E = 1.529$ ,  $N_O - N_E = 0.003$  (Larsen <sup>41</sup>);  $N_O = 1.536$ ,  $N_O - N_E =$  about 0.001 (Müller <sup>42</sup>). Pale green to colorless. Found in pegmatite, as at Gletsch, Switzerland.

**Danburite** ( $\text{CaSi}_2\text{B}_2\text{O}_8$ ) is orthorhombic dipyramidal <sup>43</sup> with  $a:b:c = 0.919:1:0.882$ . Space group  $Pnam$ ;  $a$  8.03,  $b$  8.74,  $c$  7.71 Å. U.C. 4. Crystals often prismatic with very poor 001 cleavage.  $H. = 7$ .  $G. = 3.0$ .  $F. = 3.5-4$ , giving green

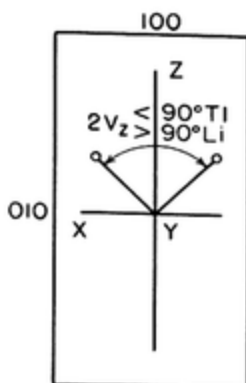


FIG. 145. The optic orientation of danburite.

flame color. Nearly insoluble in HCl. The optic plane is 001 and  $X = a$ ; on account of very strong dispersion the mineral is negative for red, yellow, and green light, but positive for blue light. See Fig. 145.

	Li	Na	Tl	CuSO <sub>4</sub> light
$(- )2V =$	$88^\circ \text{ ca.}$	$88^\circ \text{ ca.}$	$89^\circ \text{ ca.}$	$(+)2V = 89^\circ \text{ ca.}$
$N_X =$	$1.626 \text{ ca.}$	$1.630$	$1.6356 \text{ ca.}$	
$N_Y =$	$1.630-1.634$	$1.633-1.637$	$1.635-1.638$	$1.646$
$N_Z =$	$1.633 \text{ ca.}$	$1.636 \text{ ca.}$	$1.6393 \text{ ca.}$	
$N_Z - N_X =$	$0.007$	$0.006$	$0.0037$	

More precise measures on danburite (with MgO 0.76, Fe<sub>2</sub>O<sub>3</sub> plus Al<sub>2</sub>O<sub>3</sub> 1.00) from Obira, Japan, are given by Harada <sup>44</sup> as follows:

$\lambda =$	671 (Li)	589 (Na)	546	492	436	405
$2V_X =$	$88^\circ 7'$	$88^\circ 22'$	$88^\circ 55'$	$89^\circ 58'$	$91^\circ 32'$	$93^\circ 4'$
$N_X =$	$1.6275(0)$	$1.6303(2)$	$1.6324(6)$	$1.6361(0)$	$1.6416(7)$	$1.6456(6)$
$N_Y =$	$1.6304(6)$	$1.6332(7)$	$1.6354(0)$	$1.6390(1)$	$1.6445(0)$	$1.6484(3)$
$N_Z =$	$1.6332(4)$	$1.6360(8)$	$1.6382(4)$	$1.6419(1)$	$1.6475(1)$	$1.6515(3)$
$N_Z - N_X =$	$0.0057(4)$	$0.0057(6)$	$0.0057(8)$	$0.0058(1)$	$0.0058(4)$	$0.0058(7)$

Color pale wine yellow, colorless, dark yellow, yellowish brown.

<sup>41</sup> E. S. Larsen: *U. S. Geol. Surv. Bull.* 679 (1921) and 848 (1934).

<sup>42</sup> J. Königsberger and W. J. Müller: *N. Jahrb. Min., Bl. Bd.* XLIV, 402 (1921).

<sup>43</sup> J. D. H. Donnay: *Trans. Roy. Soc. Canada*, XXXIV, sect. 3, 33 (1940). Dana's  $ab2c = X\text{-ray } bac$ .

<sup>44</sup> Z. Harada: *Zeit. Krist.*, LXXIX, 349 (1931).

Danburite is found with feldspar in dolomite at Danbury, Connecticut; also in granite at Russell, New York; in pegmatite or metamorphic rocks at many other places. It is characterized by very large extinction angle, strong dispersion, and weak birefringence; it differs from topaz in the absence of good cleavage and in lower specific gravity.

**DUMORTIERITE**

ORTHORHOMBIC



$$a:b:c = 0.890:1:0.687$$

**PHYS. CHAR.** Crystals fibrous or columnar; twinning on 110 often as trillings. Distinct 100 and poor 110 cleavages; 001 parting.  $H. = 7$ .  $G. = 3.3$ .  $F. = 7$ . Insoluble even in HF.

**OPT. PROP.** The optic plane is 010;  $X = c$ . See Fig. 146. In twins the adjacent optic planes are at angles of about  $60^\circ$ . Optic angle small to moderate with strong dispersion reported sometimes as  $r < v$  and, rarely,  $r > v$ . Data follow:

									AUTHOR-
$Fe_2O_3$	$TiO_2$	$2V_X$	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$	G.	LOCALITY	ITY
1.08	0.08	$52^\circ$	1.659	1.684	1.686	0.027	?	Ashley	Walker <sup>45</sup>
?	?	$20^\circ$	1.668	1.687	1.688	0.020	?	Calif.	Wolff <sup>46</sup>
?	0.63-?	$35^\circ$ ca.	1.675	1.685	1.690	0.015	3.30	Nevada	Peck <sup>47</sup>
?	?	Sm.	1.670	1.691	1.692	0.022	?	Calif.	Larsen <sup>41</sup>

Color blue, greenish blue, reddish violet; strongly pleochroic in section with  $X =$  cobalt blue, violet, less commonly green, greenish brown, pink,  $Y =$  often colorless, pale blue, pale violet, yellow,  $Z =$  colorless, pale blue. The pleochroic colors parallel to  $X$  (= elongation) may be variable even in a single crystal, as blue, purple, red, brown, green, pink. Dumortierite inclusions in cordierite may cause pleochroic halos.

**ALTER.** Dumortierite alters rather easily to a mica, probably sericite.

**OCCUR.** It is found in pegmatite and gneiss, as at Dolní, Moravia; Kaňk, Bohemia; and Clip, Arizona.

**DIAG.** It is characterized by intense pleochroism with maximum absorption parallel to elongation, and by insolubility even in HF.

**Bavenite**  $\{Ca_4(OH)_4Si_9Al_2BeO_{24}\}$  is orthorhombic <sup>48</sup> with <sup>49</sup>  $a:b:c = 0.839:1:0.215$ . Space group  $P222$  or  $Pmm$  or  $Pmmm$ .  $a$  <sup>49</sup> 19.34,  $b$  23.06,  $c$  4.95 Å. U.C. 4. Fibers flattened on 010 with good 100 and poor 001 cleavages. Twinning on 100.  $H. = 5.5$ .  $G. = 2.74$ . The optic plane is 010;  $X = c$ .  $(+ )2V = 47^\circ$ ,  $N_X = 1.578$ ,  $N_Y = 1.579$ ,  $N_Z = 1.583$ ,  $N_Z - N_X = 0.005$ . Again: <sup>50</sup>  $(+ )2V = 60^\circ$ ,  $N_X = 1.586$ ,  $N_Y = 1.588$ ,  $N_Z = 1.593$ ,  $N_Z - N_X = 0.007$ . Color white. Found in pegmatite at Baveno, Italy.

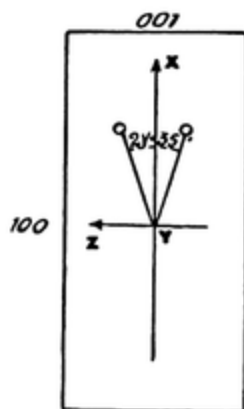


FIG. 146. The optic orientation of dumortierite.

<sup>45</sup> T. L. Walker: *Univ. Toronto Geol. Stud.*, XIV, 80 (1922).

<sup>46</sup> J. E. Wolff: *Am. Mineral.*, XV, 188 (1930).

<sup>47</sup> A. B. Peck: *Am. Mineral.*, XI, 96 (1926).

<sup>48</sup> C. J. Ksanda and H. E. Merwin: *Am. Mineral.*, XVIII, 341 (1933).

<sup>49</sup> G. F. Claringbull: *Mineral. Mag.*, XXV, 495 (1940).

<sup>50</sup> E. I. Kutukova: *Min. Abst.*, X, 247 (1948).

**Banalsite**<sup>51</sup> ( $\text{Na}_2\text{BaSi}_4\text{Al}_4\text{O}_{16}$ ) is orthorhombic with  $a:b:c = 0.853:1:1.678$ . Space group *Iba* or *Ibam*;  $a$  8.50,  $b$  9.97,  $c$  16.73 Å. U.C. 4. Good 110 and 001 cleavages.  $H. = 6$ .  $G. = 3.06$ . Decomposed by HCl. The optic plane is 100;  $X = c$ .  $(+)2V = 41^\circ$ ,  $N_X = 1.5695$ ,  $N_Y = 1.571$ ,  $N_Z = 1.5775$ ,  $N_Z - N_X = 0.008$ . Color white. Luster pearly on cleavages; may appear milky from inclusions. A feldspathoid found in a vein in manganese ore in Wales.

**Tuhualite**<sup>52</sup>  $[(\text{Na},\text{K})_2\text{Si}_{10}(\text{Al},\text{Fe})_2\text{O}_{24}]$  is orthorhombic with  $a:b:c = 0.915:1:0.512$ . Crystals prismatic with good 001, 100, and 010 cleavages.  $G. = 2.87$ . The optic plane is 010;  $X = a$ .  $(-)2V = 65^\circ 70'$ ,  $r > v$ .  $N_X = 1.601$ ,  $N_Y = 1.605$  (calc.),  $N_Z = 1.607$ ,  $N_Z - N_X = 0.006$ . Color black to dark blue with  $X =$  pale pink,  $Y =$  purple,  $Z =$  deep violet. Alters to a greenish-yellow mineral with  $2V =$  large,  $N_Z - N_X = 0.01$ , and common lamellar twinning with symmetrical extinction at  $20^\circ$ – $24^\circ$ ;  $X =$  pale yellowish green,  $Z =$  deep olive green. Found in volcanic rock on the island of Tuhua, New Zealand.

**Trimerite**<sup>53</sup>  $[(\text{Mn},\text{Ca})\text{SiBeO}_4]$  is monoclinic prismatic with  $a:b:c = 2.119:1:3.666$ ,  $\beta = 90^\circ 9'$ . Space group  $P2_1/c$ ;  $a$  16.11,  $b$  7.60,  $c$  27.86 Å. U.C. 48. Pseudohexagonal by twinning. Crystals thick six-sided prisms with distinct basal cleavage.  $H. = 6$ – $7$ .  $G. = 3.47$ .  $F. = 6$ . Soluble in HCl. The optic plane and  $X$  are nearly normal to 001.  $(-)2V = 83^\circ 29'$ ,  $N_X = 1.7148$ ,  $N_Y = 1.7202$ ,  $N_Z = 1.7253$ ,  $N_Z - N_X = 0.0105$ . Color pink; colorless in section. Found in calcite in manganese mines in Sweden.

## PETALITE

### MONOCLINIC DOMATIC



$$a:b:c = 2.298:1:2.959 \quad \beta = 112^\circ 44'$$

STRUC. Space group<sup>54</sup> *Cc*;  $a$  11.77,  $b$  5.13,  $c$  15.17 Å. U.C. 4.

PHYS. CHAR. Crystals {010} tablets or elongated parallel to  $a$ . Perfect 001 and good 101 cleavages.  $H. = 6.5$ .  $G. = 2.42$ .  $F. = 5$  (phosphorescent). Insoluble in acids, except HF.

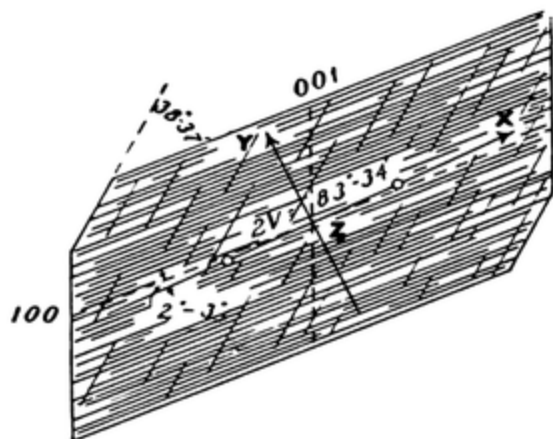


FIG. 147. The optic orientation of petalite.

OPT. PROP. The optic plane and  $Z$  are normal to 010;  $X \wedge a$  ( $=$  001 cleavage)  $= 2^\circ$  to  $8^\circ$  in the acute angle  $\beta$ . See Fig. 147. Weak crossed dispersion with  $r < v$  also weak.  $(+)2V = 83^\circ 34'$ ,  $N_X = 1.504$ ,  $N_Y = 1.510$ ,  $N_Z = 1.516$ ,  $N_Z - N_X = 0.012$ .  $F - C$  for  $N_Y = 0.007$ . Red, green, or white; colorless in thin section.

INVER. Petalite from Elba becomes uniaxial at  $1000^\circ$ – $1100^\circ$ ; then it becomes isotropic at  $1200^\circ$ ; at  $1370^\circ$  it forms a glass with  $G. = 2.29$  and  $N = 1.495$ .

OCCUR. Petalite is found in pegmatites and in some ore deposits, often associated with spodumene, tourmaline, etc., as at Peru, Maine.

<sup>51</sup> W. C. Smith, F. A. Bannister and M. H. Hey: *Mineral. Mag.*, XXVII, 33 (1944).

<sup>52</sup> P. Marshall: *Trans. Roy. Soc. New Zealand*, LXVI, 330 (1936).

<sup>53</sup> G. Aminoff: *Geol. För. Förh.*, XLVIII, 19 (1926). H. Strunz: *Min. Tabellen*, 208 (1941).

<sup>54</sup> B. Gossner and F. Muschnug: *Zeit. Krist.*, LXXIV, 62 (1930).

**DIAG.** Extinction nearly parallel to the best cleavage, which has a negative sign of elongation; a large positive optic angle; and an angle of  $114^\circ$  between two unequal cleavages are characteristic.

### FELDSPAR GROUP<sup>55</sup>

The feldspars are far more important as rock constituents than any other group of minerals; in fact they may be compared in importance in igneous rocks with all other groups combined, since they constitute nearly 60 per cent of such rocks and serve as the basis of their classification.

### Summary

The description of the feldspar group is so long that the following summary of the chief features may be useful.

**COMP.** The feldspars are aluminosilicates of potassium, sodium, or calcium (rarely barium). The chief chemical types are  $KAlSi_3O_8$  (orthoclase and microcline),  $NaAlSi_3O_8$  (albite), and  $CaAl_2Si_2O_8$  (anorthite). Natural crystals of orthoclase and of microcline usually contain 10 to 25%  $NaAlSi_3O_8$ . Calcium and aluminum proxy for sodium and silicon to form mix-crystals in all proportions, which are called plagioclase; these also contain 5 to 15%  $KAlSi_3O_8$  in most cases. See pages 263-265; also 296-302.

**PHYS. CHAR.** Crystals of orthoclase are monoclinic, and those of plagioclase are triclinic, but the forms are, nevertheless, very similar with angles differing only  $3^\circ$  or  $4^\circ$ . All feldspars have good cleavages parallel to 001 and 010 making an angle of  $90^\circ$  in orthoclase and  $93^\circ 34'$  to  $94^\circ 12'$  in plagioclase. The basal cleavage is "perfect" and easily obtained; the other is good, but not so distinct. Other cleavages exist only in traces. The feldspars exhibit many kinds of twinning; in general, orthoclase twins consist of only two (rarely three) parts, while microcline and plagioclase twins are multiple and lamellar, microcline showing a fine cross-grating of twinning bands. The specific gravity of ordinary feldspars ranges from 2.5 to 2.8, and the hardness from 6 to 6.5. Fusion occurs at  $1100$  to  $1550^\circ$ . Except for anorthite, ordinary feldspar is insoluble in HCl. See pages 265-273.

**OPT. PROP.** The feldspars have low relief ( $N = 1.52$  to  $1.58$ ), weak birefringence ( $N_z - N_x = 0.006$  to  $0.013$ ), and weak dispersion. They are all biaxial and of large optic angle except for one type of  $KAlSi_3O_8$ ; the sign is negative except in certain varieties of plagioclase. The extinction angles in sections of any known orientation are very useful in distinguishing between various kinds of feldspar; some of the most important extinction angles are given in Fig. 148. Feldspars are naturally colorless and glassy but are often clouded by fractures and stained by impurities of various kinds. See pages 273-276; also 280-296.

**ALTER.** The hydration of feldspars may lead to the formation of sericite, kaolinite, zeolites, or similar minerals. Many other kinds of alteration products are known, the type produced depending on the conditions of temperature, pressure, and types of solutions to which the feldspars have been subjected. Feldspars are less stable than quartz, but more stable than olivine, nepheline, etc. See pages 276-279.

**OCCUR.** Feldspars are abundant in metamorphic as well as in igneous rocks, and

<sup>55</sup> The newly discovered orthorhombic "feldspar" banalsite is not included in the following description of the group. See page 260.

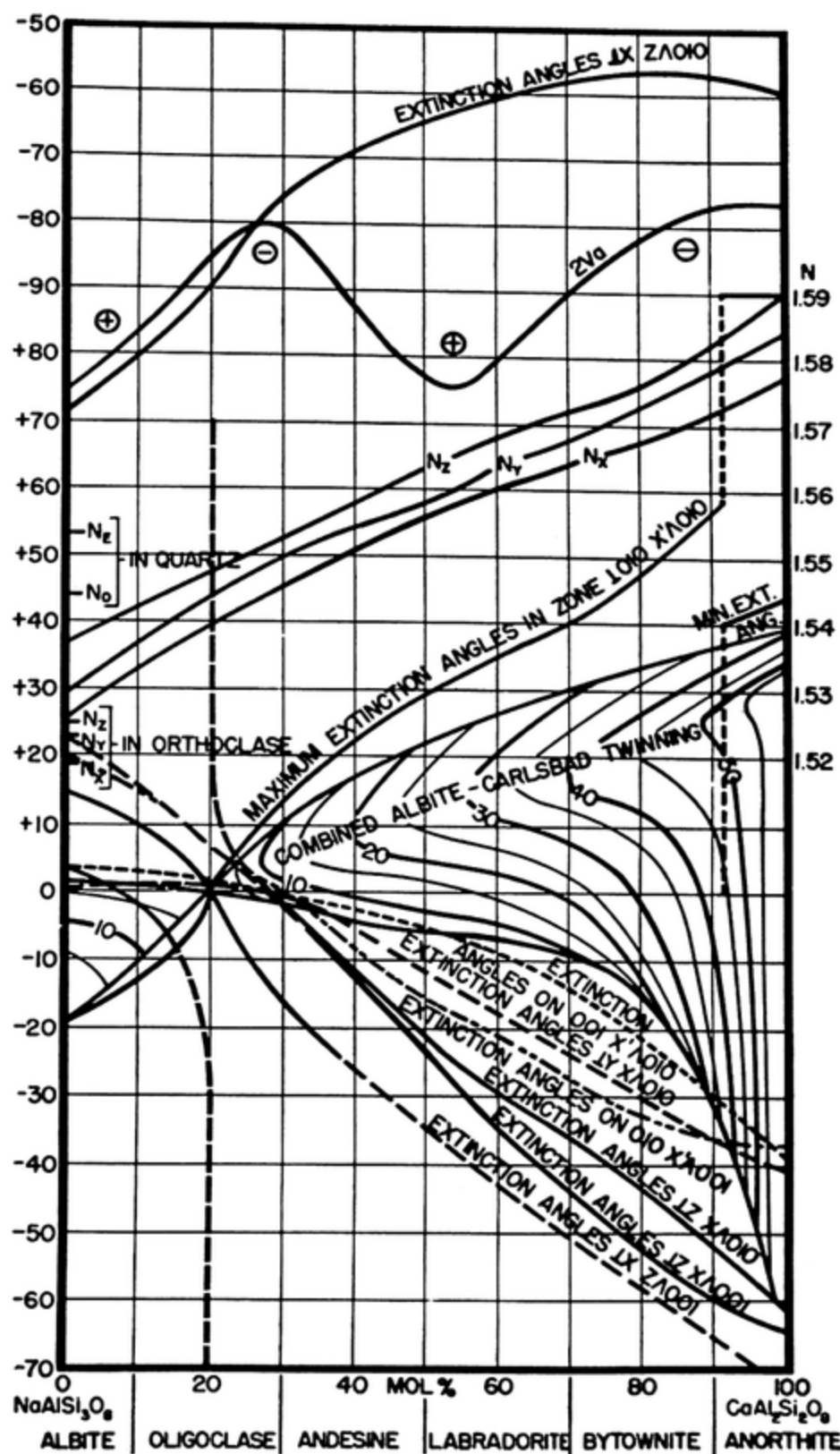


FIG. 148. Properties of plagioclase.



they are also found in some sedimentary rocks. They form a large part of nearly all igneous rocks. See pages 279, 305-308, 310, 312, 330.

DIAG. Data for distinguishing between the various kinds of feldspars by the most important optical methods are summarized in Fig. 148. See also pages 279, 296, 305-330.

CHEM. COMP. The feldspars, aside from the rare and unimportant types containing barium, belong to a three-component system whose end-members are  $KAlSi_3O_8$  (the orthoclase molecule = Or),  $NaAlSi_3O_8$  (pure albite = Ab), and  $CaAl_2Si_2O_8$  (pure anorthite = An). Ab and An are mutually soluble in all proportions in the crystal state as well as in the liquid state. These form a continuous series known as plagioclase. All proportions of Or and Ab are mutually soluble in crystals at high temperature but are mutually soluble only in limited proportions at low temperature. But Or and An are nearly immiscible as crystals even at high temperature, and the simultaneous crystallization of orthoclase (or microcline) and calcic plagioclase is very common in nature. Crystals containing several different proportions of Or and barium feldspar (celsian = Cn) have been found in nature, but a complete continuous series is not demonstrated and will not be assumed.

The chemical composition of the pure molecules and of crystals containing two molecules in certain simple ratios is given in the following table:

Molecule	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	BaO
Cn	32.0	27.2				41.8
Or <sub>50</sub> Cn <sub>50</sub>	45.9	23.4			7.2	23.5
Or <sub>80</sub> Cn <sub>20</sub>	56.5	20.6			12.6	10.3
Or	64.7	18.4			16.9	
Or <sub>80</sub> Ab <sub>20</sub>	65.6	18.5		2.4	13.5	
Or <sub>50</sub> Ab <sub>50</sub>	66.8	18.9		5.9	8.4	
Or <sub>20</sub> Ab <sub>80</sub>	68.0	19.2		9.4	3.4	
Ab	68.8	19.4		11.8		
Ab <sub>80</sub> An <sub>20</sub>	63.3	23.1	4.3	9.3		
Ab <sub>60</sub> An <sub>40</sub>	58.1	26.6	8.4	6.9		
Ab <sub>40</sub> An <sub>60</sub>	53.0	30.0	12.4	4.6		
Ab <sub>20</sub> An <sub>80</sub>	48.0	33.4	16.3	2.3		
An	43.2	36.7	20.1			

Again excluding the rare types containing barium,<sup>56</sup> nearly all natural feldspars contain appreciable amounts of a third component in addition to the two chief components.<sup>57</sup> Therefore, although the feldspars of

<sup>56</sup> These, also, are more complex than is indicated by describing them as belonging to the series Or-Cn, since they often contain a little Na, etc.

<sup>57</sup> Besides the three chief components (Or, Ab, and An) some feldspars contain very small amounts of still other molecules, notably  $RbAlSi_3O_8$ ,  $CsAlSi_3O_8$ ,  $LiAlSi_3O_8$ ,  $Na_2Al_2Si_2O_8$ (?). A strontium feldspar has been made artificially.

rocks are commonly described as orthoclase (or microcline, or anorthoclase) and plagioclase (of some kind), they are really not one- or two-component substances as indicated by these names but are three-component crystal solutions. This is well illustrated in Fig. 149, which shows the results of plotting nearly a thousand analyses of feldspars on

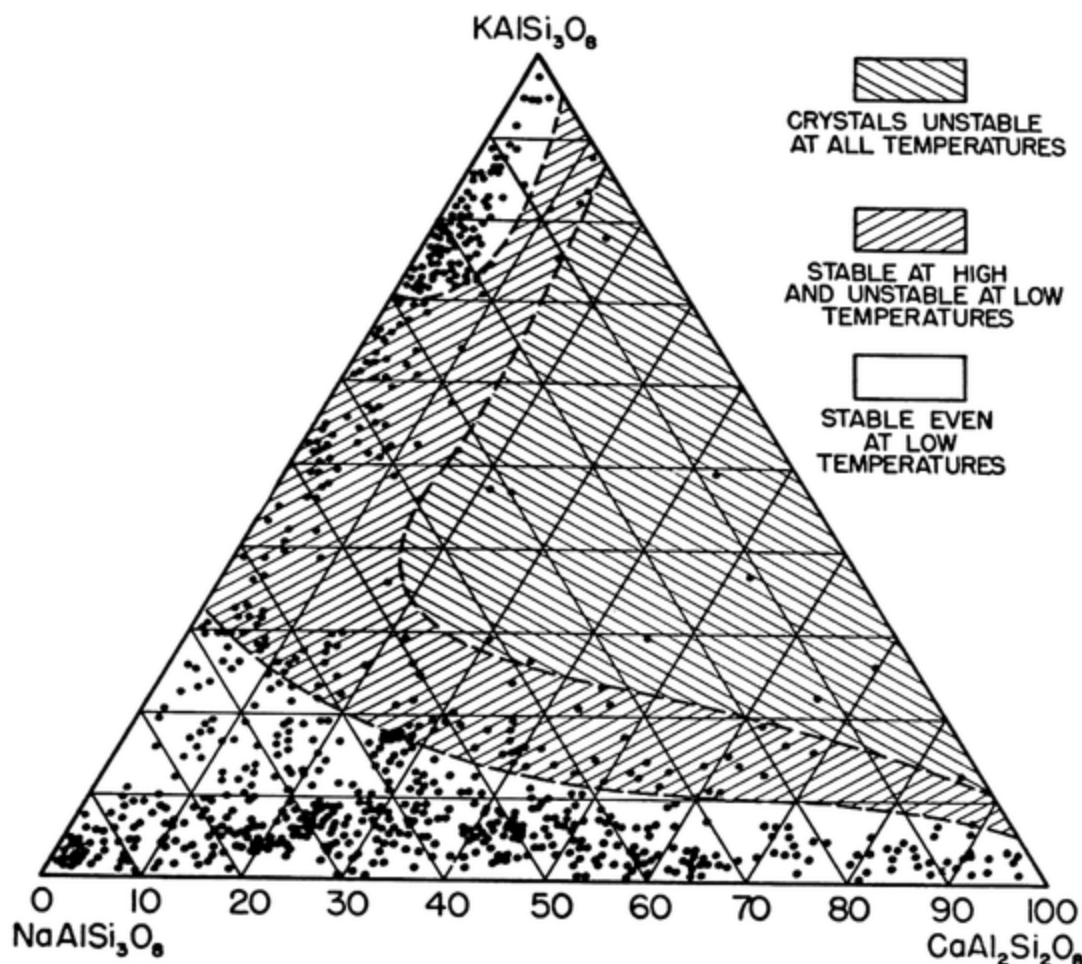


FIG. 149. Variations in composition in feldspar. After H. L. Alling: *Jour. Geol.*, XXIX, 193 (1921). Stability areas added by the author.

a three-component diagram. To the original diagram prepared by Alling the author has added shading to express his ideas of the approximate limits of stable solid solutions at various temperatures. Crystals of composition in the intermediate zone are believed to be stable at high temperatures and unstable, or metastable, at low temperatures. Sometimes such crystals seem to remain homogeneous (metastable) at low temperatures; occasionally, they seem to separate into distinct, but intimately intergrown, parts on cooling, the whole mass then being known as *perthite*. This change from a single crystal structure to two intergrown crystal structures of different kinds may occur even without

separation into distinct parts, visibly different, as shown by the tests of Kozu and Suzuki,<sup>58</sup> who found that X-ray patterns from *moonstone* indicated two crystal structures at ordinary temperatures (one corresponding with orthoclase and the other with albite), and that these approach each other above 500° and coalesce at high temperatures.

**CRYSTAL FORM.** The similarity of crystal form of all the feldspars, both monoclinic and triclinic, is shown in the following table. Here, and in other tables which follow, the composition is commonly expressed in terms of the chief feldspar molecules, which are: anorthite ( $CaAl_2Si_2O_8 = An$ ), albite ( $NaAlSi_3O_8 = Ab$ ), orthoclase ( $KAlSi_3O_8 = Or$ ), and celsian ( $BaAl_2Si_2O_8 = Cn$ ).

## CRYSTALLOGRAPHY OF THE FELDSPARS

Name	$a:b:c$	$\alpha$	$\beta$	$\gamma$	$001 \wedge 010$	Approximate Composition
Celsian	0.657:1:0.554	90°	115° 2'	90°	90°	Cn
Adularia <sup>59</sup>	0.654:1:0.554	90°	116° 3'	90°	90°	Or
Sanidine <sup>60</sup>	0.652:1:0.551	90°	115° 35'	90°	90°	Or
Microcline <sup>61</sup>	0.664:1:0.555	89° 19'	115° 50'	92° 10'	90° 17'	Or
Anorthoclase	0.647:1:0.552	90° 30'	116° 18'	90° ±	90° ±	(Ab, Or)
Plagioclase						
Albite <sup>62</sup>	0.633:1:0.558	94° 31'	116° 38'	87° 31'	86° 26'	Ab
Oligoclase	0.632:1:0.553	93° 31'	116° 26'	89° 31'	86° 18'	Ab <sub>80</sub> An <sub>20</sub>
Andesine	0.635:1:0.552	93° 27'	116° 15'	89° 58'	86° 10'	Ab <sub>60</sub> An <sub>40</sub>
Labradorite	0.637:1:0.555	93° 26'	116° 6'	90° 15'	86° 3'	Ab <sub>40</sub> An <sub>60</sub>
Bytownite		93° 22'	116° 0'	90° 41'	85° 56'	Ab <sub>20</sub> An <sub>80</sub>
Anorthite <sup>62</sup>	0.635:1:0.551	93° 5'	115° 54'	91° 34'	85° 48'	An

Feldspar crystals are often short prismatic in habit, somewhat flattened parallel to 010, as in Figs. 150–153; they are also frequently elongated parallel to  $a$ , the crystals then appearing to be prismatic through development of 001 and 010, the real prism faces (110) being quite small, as shown in Figs. 154 and 155. Feldspar microlites are usually of the form just described; when somewhat larger they may be thin laminae parallel to 010, as in Fig. 156. Anorthoclase is commonly elongated parallel to the vertical axis. Plagioclase (the Ab-An series) is distinctly triclinic, yet the angles  $\alpha$  and  $\gamma$  vary only a little from 90°.

<sup>58</sup> *Sci. Rep. Tohoku Univ. Sendai*, Ser. III, I, 19 (1921).

<sup>59</sup> W. H. Taylor, J. A. Darbyshire and H. Strunz: *Zeit. Krist.*, LXXXVII, 464 (1934).

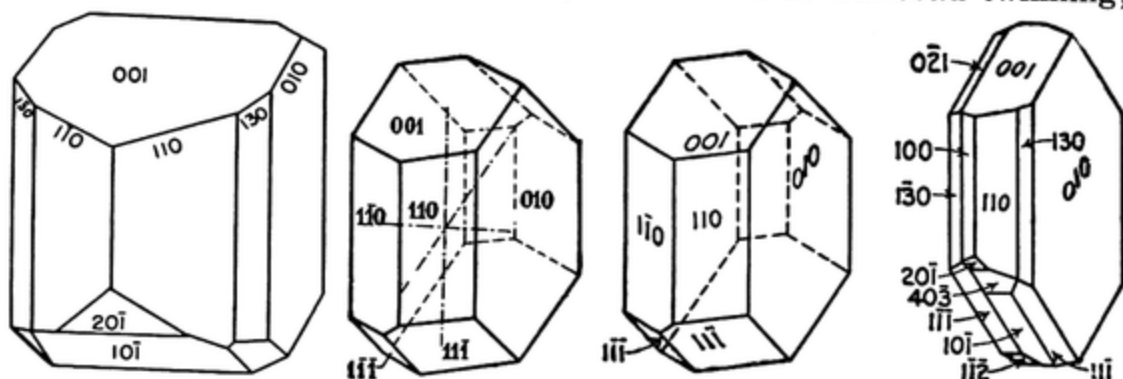
<sup>60</sup> E. Schiebold: *Zeit. Krist.*, LXVI, 488 (1928).

<sup>61</sup> O. B. Bøggild: *Zeit. Krist.*, XLVIII, 466 (1911).

<sup>62</sup> E. Schmidt: *Chem. Erde*, I, 351 (1919).

The forms are therefore very similar to those of the monoclinic feldspars. Plagioclase is sometimes elongated parallel to  $b$ , a condition commonly found in the *pericline* variety of albite; when twinned on the axis  $b$ , the units are thin lamellar and produce striations on 100 and 010, which may be found in any kind of plagioclase.

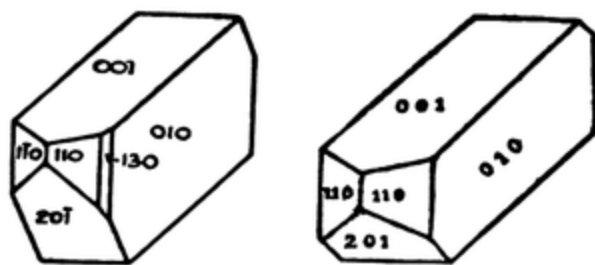
**TWINNING.** All the feldspars are subject to very common twinning. The usual type in monoclinic feldspar is known as Carlsbad twinning;



FIGS. 150-153. Simple crystal habits of feldspar.

other types include the Manebach and Baveno. In triclinic feldspars the albite type of twinning is nearly always present and other types are not rare, especially the pericline and Carlsbad.

In Carlsbad twinning the twins are united by some plane, usually 010, parallel to the vertical axis, while the twinning axis may be considered



FIGS. 154, 155. Feldspar crystals elongated parallel to the axis  $a$ .

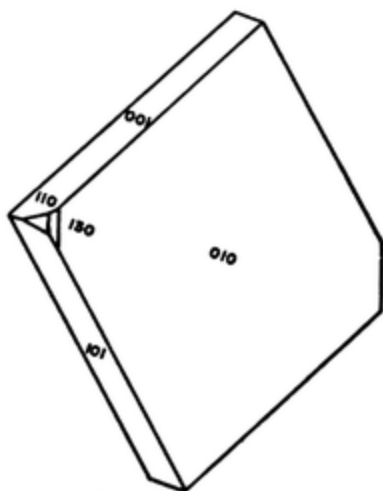


FIG. 156. Feldspar microlite extended parallel to 010.

to be  $c$ , or a line normal to 100. Such twins may be merely in contact, as in Fig. 157, or show more or less interpenetration, as in Fig. 158. In a thin section of a Carlsbad twin the 010 cleavage in one part is parallel with that in the other part, and the basal cleavages form oblique angles with one another. If the section is normal to 010, the 001 and 010

cleavages will be exactly, or very nearly, at right angles. Carlsbad twins are almost invariably composed of only two parts; this fact is of considerable importance in distinguishing macroscopically, and in a rapid preliminary way microscopically, between orthoclase and plagioclase. Multiple lamellar twinning is nearly always present in plagioclase.

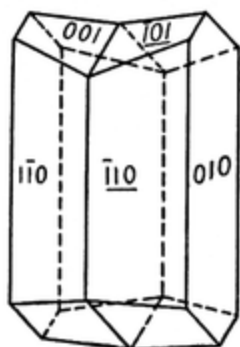


FIG. 157. Contact Carlsbad twin of albite.

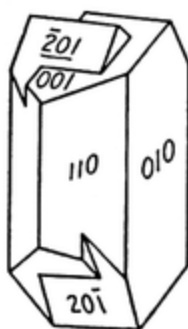


FIG. 158. Partial penetration Carlsbad twin of orthoclase.

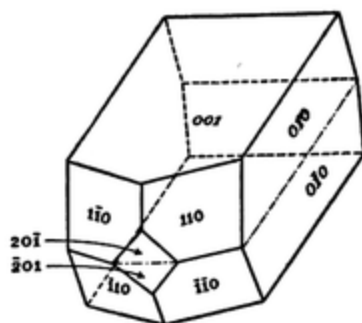


FIG. 159. Manebach twin of orthoclase.

Manebach twins have the basal plane as the twinning plane (Fig. 159) and also, usually, as the composition face. The 001 cleavages of one part are parallel to the same cleavages of the other part. The same is true of 010 cleavages if the feldspar is monoclinic.

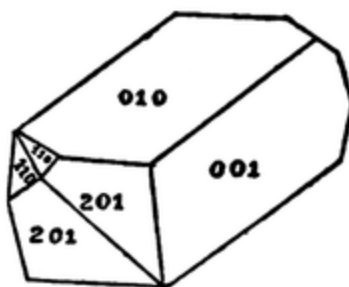


FIG. 160. Baveno twin of orthoclase.

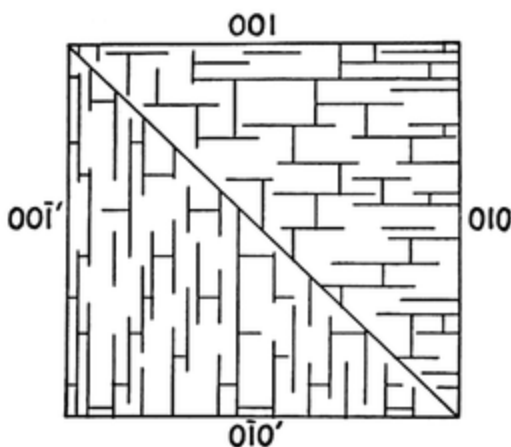
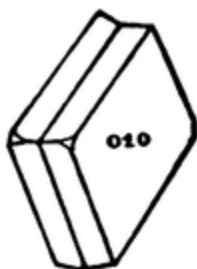
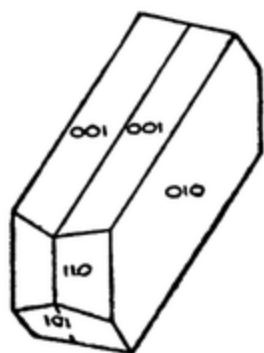


FIG. 161. Section of a Baveno twin cut normal to the axis  $a$ .

In Baveno twins the twinning axis is normal to 021 which is the composition face. Such twins are elongated parallel to  $a$  and often flattened parallel to 001. In the absence of flattening, they are nearly square in cross section as seen in Fig. 160, since  $001 \wedge 021$  is nearly  $45^\circ$ , being  $44^\circ 56'$  in orthoclase and  $46^\circ 46'$  in albite. Sections across such twins present square or rhombic outlines, the cleavages being paral-

lel to the sides, and the twinning line being a diagonal from corner to corner, as shown in Fig. 161.

Albite and pericline types of twinning are impossible in monoclinic crystals but are very important in plagioclase. In albite twinning both the composition face and twinning plane are 010. Simple albite twins are shown in Figs. 162-164. This type of twinning is nearly always



FIGS. 162, 163. Simple albite twins of feldspar.

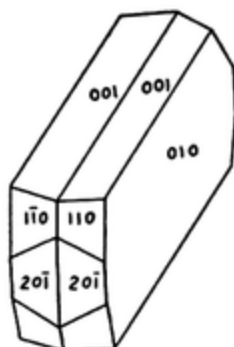


FIG. 164. Simple albite twin of feldspar.

polysynthetic and lamellar, producing striations on 001 parallel to 010; it would be perfectly parallel growth (and not twinning) in orthoclase. Albite twinning is characteristic of plagioclase, in which it is only rarely lacking.

In pericline twins (Fig. 165) the twinning axis is the axis  $b$ , while the composition face is the *rhombic section*, which is the section made by a plane passing through the crystal parallel to the axis  $b$  in such a direction that it makes equal angles with 110 and  $1\bar{1}0$ . The position of this rhombic section<sup>63</sup> and the consequent direction of the twinning bands on 010 change rapidly with small changes in the value of  $\gamma$ . In 010 these twinning bands vary from parallel to the basal cleavage in one type of andesine to an angle of  $+21^\circ$  with 001 in albite and to  $-18^\circ$  with 001 in anorthite, as shown in Fig. 166.

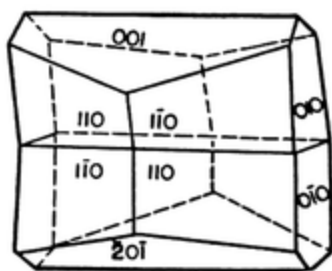


FIG. 165. Simple pericline twin of albite.

Except rarely in albite, pericline twinning is multiple, fine lamellar, and invisible without the microscope.

In microcline, and apparently in anorthoclase, this type of twinning exists with a composition face which makes a large angle with 001, as

<sup>63</sup> The position varies with the temperature of formation of the crystal (as well as with its composition) and may therefore be used as a sort of "geologic thermometer." See O. Mügge: *Zeit. Krist.*, LXXV, 337 (1930).



shown in Fig. 166. Microcline is characterized by the nearly constant presence of two intersecting sets of fine lamellar twinning, any single twinning band usually tapering out at both ends, one set being albite twinning and the other the twinning just described. Anorthoclase usually has a similar quadrillage, though it is less distinct, being extremely fine and poorly defined. In anorthoclase one set of twinning lines is of the albite type; the other is either pericline twinning at  $-4^\circ$  to  $-8^\circ$  with 001, or at  $-75^\circ$  to  $-78^\circ$  with 001.

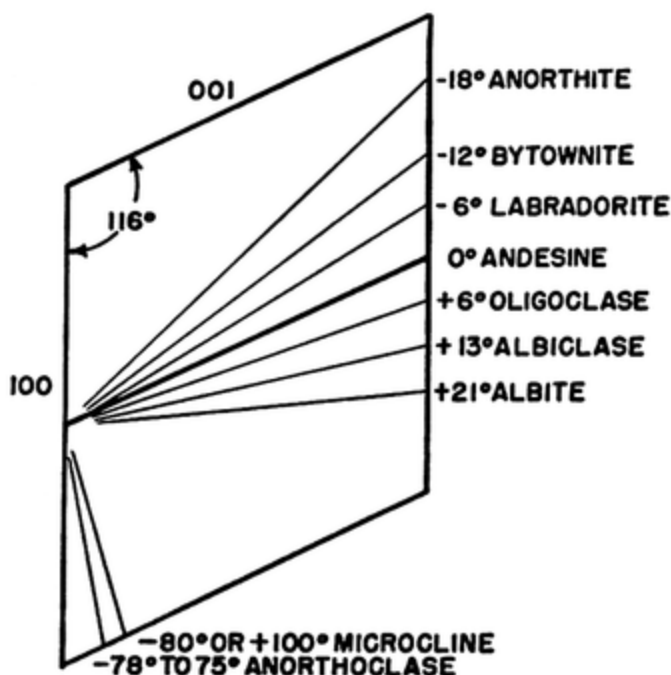


FIG. 166. Position of composition face of pericline twinning in triclinic feldspars.

Plagioclase very often exhibits Carlsbad twinning, with or without albite twinning; other types, which are found less commonly in plagioclase, include Manebach and Baveno twinning.

In thin section there is not much difference between the appearance of the various types of multiple twinning in various feldspars, but as a generalization it may be said that multiple albite twinning bands are usually fine and far apart in albite, clear and of regular width (one set being wide and the other very fine) in oligoclase, clear and well defined in labradorite, but of varying widths, and broad and regular in anorthite. Pericline twinning bands are often present only in certain ones of the albite bands; pericline twinning also occurs without albite twinning; therefore it is important to note the microscopic distinctions between the two types, which may be summarized as follows:

## Albite Twinning

Very common

Parallel to 010 cleavage

Parallel to Carlsbad twinning

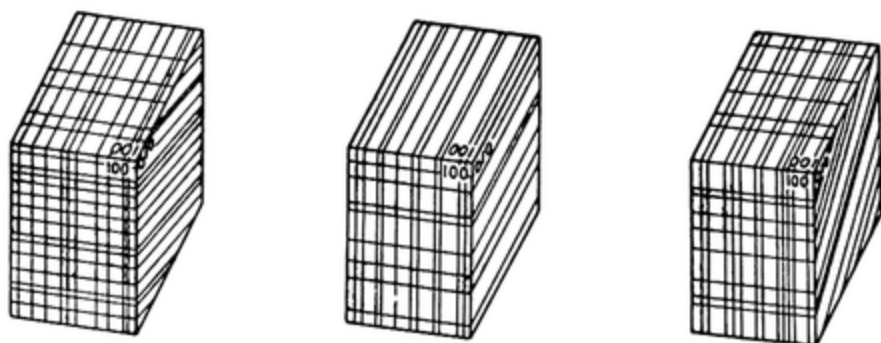
Negative elongation (except in anorthite)

## Pericline Twinning

Not rare

At  $0^\circ$  to  $21^\circ$  with 001 cleavageAt  $0^\circ$  to  $21^\circ$  with (rare) Manebach twinningElongation  $\pm$ 

Albite and especially pericline twinning bands are so fine that they are frequently invisible without the microscope; their positions in simple crystals are shown in Fig. 167 for albite, Fig. 168 for andesine, Fig. 169 for anorthite,



FIGS. 167-169. Albite twinning and pericline twinning striations on the pinacoid faces of albite (167), andesine (168), and anorthite (169); albite striations are vertical and pericline striations are horizontal on 100. Acline twinning striations on all plagioclases have the same position as pericline striations on andesine.

and Fig. 169 for anorthite. The front face 100 is rarely seen in nature, being replaced by prism faces.

In summary, orthoclase often occurs in simple twins, but never in polysynthetic twins; microcline is nearly always polysynthetically twinned in two directions, giving a fine grating structure between crossed nicols; plagioclase is nearly always multiply twinned on the albite (or pericline) law.

There are still other types of twinning in feldspar, and all these types have been classified<sup>61</sup> as follows:

1. *Normal twins*, in which the twinning axis is normal to the composition face, which is an important crystal face, namely, 010 in albite twinning, 001 in Manebach twinning, 021 in Baveno twinning, and 100 in twinning expected but not yet found.

2. *Parallel twins*, in which the twinning axis is parallel to the composition plane, which may be a crystal face or vary notably from such a

<sup>61</sup> See L. Duparc and M. Reinhard: *Mém. Soc. Phys. Hist. Nat. Genève*, XL, fasc. 1 (1924), for an elaborate treatise on feldspars, based in large part on the work of Fedorov.

face. For example, the twinning axis is  $c$  and the composition face is 010 in "Carlsbad A" twinning; the twinning axis is  $c$  and the composition face is 100 (or near it) in "Carlsbad B" twinning; the twinning axis is  $b$  and the composition face is 001 or within  $21^\circ$  of that face in the zone [010] parallel to the axis  $b$  in pericline twinning.

3. *Complex twins*, which consist of aggregates showing both normal and parallel twins having the same composition face. For example, a crystal may have Carlsbad A and also albite twinning; the composition face being 010 for each, the aggregate is a "complex" twin. Furthermore, it is customary to designate the first part as 1, the part in normal twinning relation to it as  $1'$ , the part in parallel twinning relation with it as 2, and the part in normal twinning relation with 2 as  $2'$ , which is in parallel twinning relation with  $1'$ . In some cases such groups may be incomplete, showing only 1 and  $2'$ , or  $1'$  and 2. Expressed in another way, such incomplete groups may be considered parallel twins in which the twinning axis is parallel to the composition face, but normal to the twinning axis of the type of parallel twinning involved in a corresponding complete group. For example, a part 1 may be twinned on 010 with  $1'$  (albite type) and twinned on  $c$  with 2 (Carlsbad A), the part 2 being twinned on  $c$  with  $2'$  (albite type), all parts having 010 as the composition plane. In the absence of some parts, one may consider that part 1 is twinned with part  $2'$  (also  $1'$  with 2) on an axis in 010 normal to  $c$ .

The different kinds of twinning in feldspars are summarized in Tables I-III.

#### I. NORMAL TWINNING

Twinning Axis	Composition Face	Name	Remarks
$\perp 010$	010	Albite	Usually multiple; very common
$\perp 001$	001	Manebach	Usually simple; not rare
$\perp 021$	021	Baveno	Usually simple; uncommon

#### II. PARALLEL TWINNING

$c$	010	Carlsbad A	Usually simple; very common; often associated with albite type
$c$	100	Carlsbad B	Composition face varies somewhat in the zone parallel to $c$
$a$	001	Ala A	Usually multiple; often associated with Manebach type
$a$	010	Ala B	Often associated with albite type
$b$	001	Acline A	Associated with Manebach type
$b$	Rhombic section	Pericline	Alone or with albite type; fairly common

## III. COMPLEX TWINNING

$c$ and $\perp 010$ or $\perp c$ in 010	010	Albite— Carlsbad A	Common; may be multiple or have only 1, 2 and 2' or only 1 and 2'
$a$ and $\perp 010$ or $\perp a$ in 010	010	Albite— Ala B	Not common
$a$ and $\perp 001$ or $\perp a$ in 001	001	Manebach— Ala A	Not common
$b$ and $\perp 001$ or $\perp b$ in 001	001	Manebach— Acline A	Not very rare in labradorite and related plagioclases

It may be added that all sorts of combinations of the various types of twinning are found, such as Carlsbad with pericline, albite with



FIG. 170. Stereographic projection of the optic elements in plagioclase on a plane normal to the axis  $c$ . (After Duparc and Reinhard.)

Baveno, etc. The term "complex twinning" should be restricted to aggregates of two types having the same composition face.

Studies of the relative abundance of the various types of twinning show that those with 010 as the composition plane are decidedly most frequent, followed by the pericline type. In microlites, Carlsbad alone

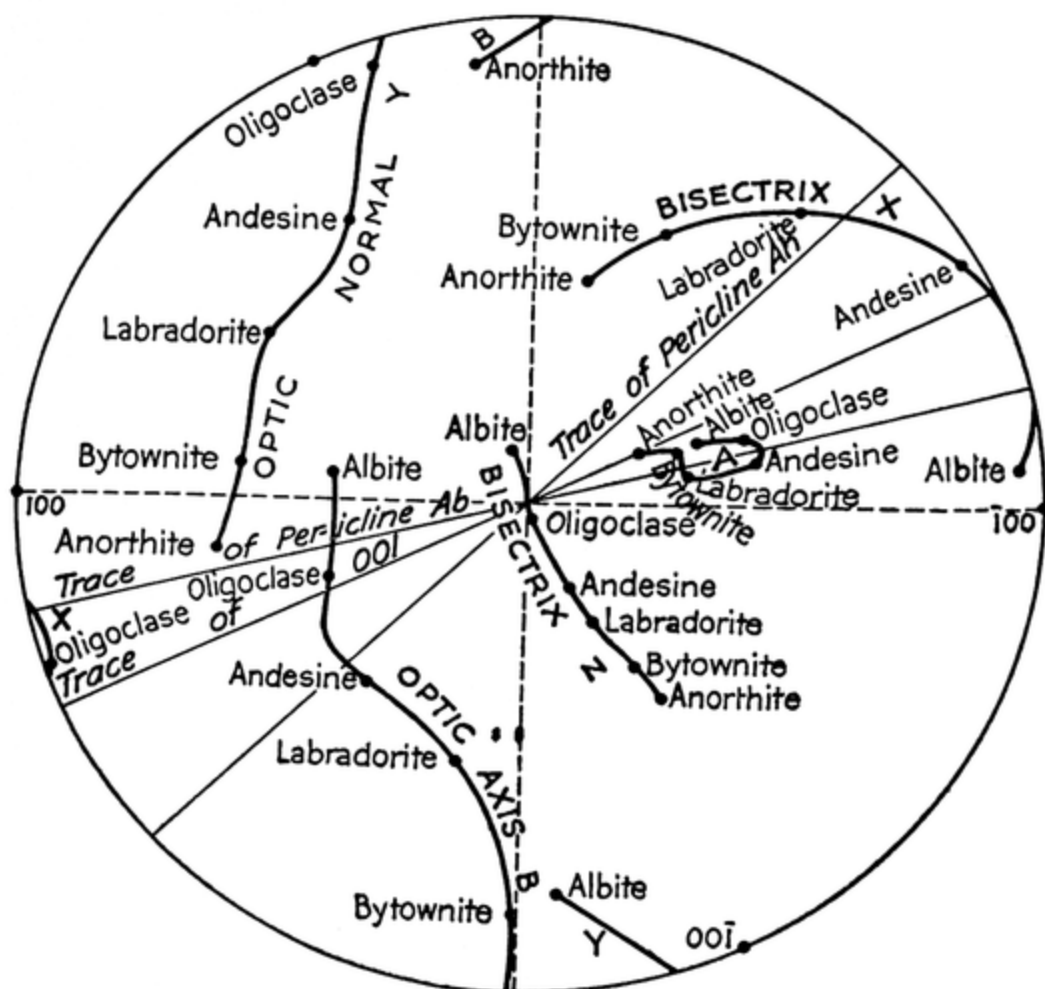


FIG. 171. Stereographic projection of the optic elements in plagioclase on a plane normal to the axis  $b$ . (After Duparc and Reinhard.)

or Carlsbad-albite is as common as albite alone, so that determinations based on microlites should be checked carefully.

**OPTIC PROPERTIES.** All feldspars are biaxial and colorless in thin section. Most of the feldspars have a large optic angle, the sign of which is either positive or negative. Dispersion varies in different types but is always too weak to give visible effects in thin section (incomplete extinction in sections normal to an optic axis is due in part to dispersion). The refringence is low in all kinds of feldspar, and the birefringence is weak, except in anorthite, in which it is moderate.

The optic orientation is different in various kinds of feldspar and is extremely important in distinguishing between them microscopically. In potash feldspar (adularia and microcline) the optic plane is exactly or nearly normal to 010, and nearly parallel with the base 001, while Z is exactly or nearly normal to 010, X is nearly parallel with 001, and Y

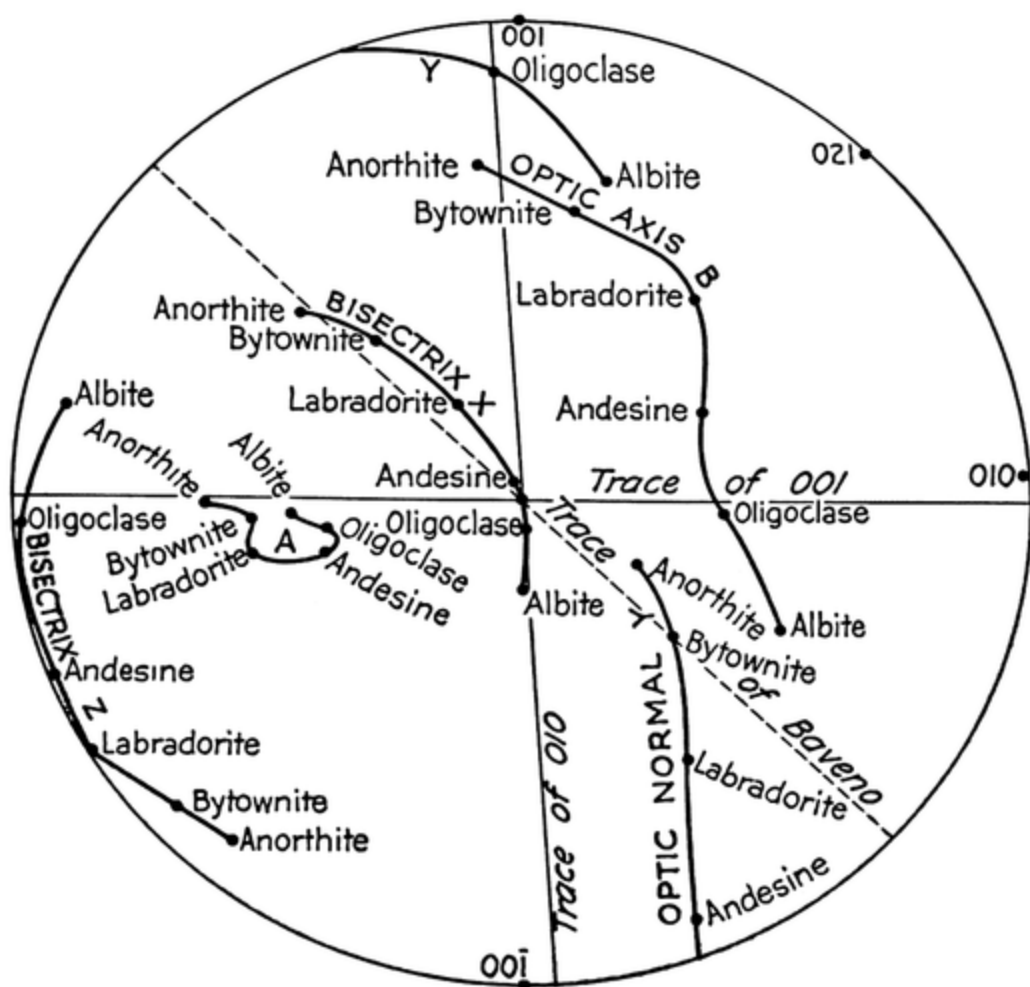


FIG. 172. Stereographic projection of the optic elements in plagioclase on a plane normal to the axis *a*. (After Duparc and Reinhard.)

is nearly normal to 001. However, adularia inverts at about  $1100^{\circ}$  to a high-temperature form (sanidine) in which the optic plane is 010 and X makes an angle of about  $+5^{\circ}$  with the axis *a*. In plagioclase the position of the optic elements is varied. It is shown in Fig. 170 as projected on a plane normal to the axis *c*, in Fig. 171 as projected on 010, and in Fig. 172 as projected on a plane normal to the axis *a*. From albite to anorthite there is a gradual rotation of the optic plane in a direction anti-clockwise about a line nearly parallel with the optic axis A, which is



nearly normal to the plane  $\bar{2}41$ , the whole movement amounting to about  $110^\circ$ .

The optic angle is about  $70^\circ$  in adularia and about  $80^\circ$  in microcline, but it is only about  $40^\circ$  in anorthoclase and still less in the high-temperature phase of  $KAlSi_3O_8$  called sanidine. In all potash feldspars the optic sign is negative.<sup>65</sup> In plagioclase the optic angle is  $71^\circ$  about Z in albite and increases to nearly  $100^\circ$  about Z (therefore negative) in oligoclase of composition about  $Ab_{75}An_{25}$ , then decreases to about  $75^\circ$  in labradorite of composition  $Ab_{45}An_{55}$ , and finally increases again to more than  $100^\circ$  about Z (again negative) in anorthite. These changes are shown in Fig. 148; the optic angle passes through  $90^\circ$  three times in this series. The optic sign is positive in celsian, albite, albitoclase, andesine, and labradorite, and negative in other types of feldspar.

OPTIC ANGLE, SIGN, DISPERSION AND SPECIFIC GRAVITY OF FELDSPARS

Name	2E	2V	Sign	Dispersion		G.
				Axial	Ellipsoidal	
Celsian (Cn)	$180^\circ+$	$86.5^\circ$	+	?	Indistinct	3.384
Hyalophane ( $Or_{80}Cn_{20}$ )	$150^\circ$	$76^\circ$	-	$r > v$	Horizontal, distinct	2.73
Orthoclase (Adularia) (Or)	$110^\circ \pm$	$60^\circ \pm$	-	$r > v$	Horizontal, distinct	2.57
Sanidine (Or)	$0-50^\circ$	Small	-	$\begin{cases} r > v \\ r < v \end{cases}$	Inclined, weak	2.56
Anorthoclase (Ab,Or)	$45-90^\circ$	$32-54^\circ$	-	$r > v$	Horizontal, weak	2.58
Microcline (Or)	$180^\circ \pm$	$83^\circ \pm$	-	$r > v$	Horizontal	2.55
Sodian microcline (Or,Ab)	$100^\circ \pm$	$60^\circ \pm$	-	$r > v$	Horizontal	2.57
Plagioclase						
Albite ( $Ab_{100}An_0$ )	$125^\circ$	$71^\circ$	+	$r < v$	Horizontal, very weak	2.61
Oligoclase ( $Ab_{80}An_{20}$ )	$180^\circ+$	$86^\circ$	-	$r > v$	Horizontal and inclined	2.64
Andesine ( $Ab_{60}An_{40}$ )	$180^\circ+$	$89^\circ$	+	$r > v$	Horizontal and inclined	2.67
Labradorite ( $Ab_{40}An_{60}$ )	$140^\circ$	$77^\circ$	+	$r > v$	Crossed and inclined	2.70
Bytownite ( $Ab_{20}An_{80}$ )	$180^\circ+$	$83^\circ$	-	$r < v$	Horizontal and inclined	2.73
Anorthite ( $Ab_0An_{100}$ )	$160^\circ$	$77^\circ$	-	$r < v$	Horizontal and inclined	2.76

Refringence is low in all the feldspars except in anorthite and celsian, in which it is moderate. The refringence is about the same as that of Canada balsam (which has  $N = 1.53-1.54$ , or with xylol as low as 1.52). The birefringence of feldspars is weak except for celsian and anorthite which have moderate birefringence; it varies from 0.005 in some hyalophane through 0.007 in potash feldspar and andesine to 0.011 in albite and celsian and 0.013 in anorthite. Data are summarized in the table.

<sup>65</sup> Positive varieties of orthoclase and of microcline have been reported, but they are rare.

## REFRINGENCE AND BIREFRINGENCE OF THE FELDSPARS

Name	Comp.	N <sub>X</sub>	N <sub>Y</sub>	N <sub>Z</sub>	N <sub>Z</sub> - N <sub>Y</sub>	N <sub>Y</sub> - N <sub>X</sub>	N <sub>Z</sub> - N <sub>X</sub>
Celsian	Cn	1.5835	1.5886	1.5941	.0055	.0051	.0106
Hyalophane	Or <sub>80</sub> Cn <sub>20</sub>	1.534	1.538	1.540	.002	.004	.006
Orthoclase	Or	1.5190	1.5237	1.5260	.0023	.0047	.0070
Microcline	Or	1.5224	1.5264	1.5296	.0032	.0040	.0072
Anorthoclase	(Ab, Or)	1.5234	1.5294	1.5305	.0011	.0060	.0071
Plagioclase							
Albite	Ab <sub>100</sub> An <sub>0</sub>	1.525	1.529	1.536	.007	.004	.011
Oligoclase	Ab <sub>80</sub> An <sub>20</sub>	1.5585	1.5428	1.5465	.0037	.0043	.0080
Andesine	Ab <sub>60</sub> An <sub>40</sub>	1.5500	1.5533	1.5570	.0037	.0033	.0070
Labradorite	Ab <sub>40</sub> An <sub>60</sub>	1.5398	1.5629	1.5678	.0049	.0031	.0080
Bytownite	Ab <sub>20</sub> An <sub>80</sub>	1.5670	1.5720	1.5760	.0040	.0050	.0090
Anorthite	Ab <sub>0</sub> An <sub>100</sub>	1.5755	1.5832	1.5885	.0053	.0077	.0130
Quartz		1.5443	1.5534				.0091
Canada balsam							1.54 ± .01 (with xylol 1.52-1.53)
Kollolith							1.52-1.534

**INVERSION.** Potash feldspar,  $\text{KAlSi}_3\text{O}_8$ , exists in nature in three crystal phases: the triclinic phase is called microcline; the two monoclinic phases are both known as orthoclase. The low-temperature phase of orthoclase, called adularia, inverts at about  $900^\circ$  to the high-temperature form, called sanidine. The reverse inversion does not readily take place, and so sanidine is found in many volcanic rocks. The stability relations between orthoclase and microcline are not known, but shearing stresses seem to favor inversion of orthoclase to microcline.

**INCLUSIONS.** Feldspars may contain inclusions, either gaseous, liquid, or solid, which are occasionally regularly placed; but in general these are not at all characteristic. However, inclusions are sometimes found which are more or less characteristic of certain types of feldspar; they will be mentioned in the detailed descriptions.

**ALTERATIONS.** Feldspars alter in many different ways, which may be classified as follows, although the natural conditions leading to alterations are too complex to permit any simple classification, and the following tabulation is intended only as a general outline of the major factors involved.

I. Alterations in the zone of katamorphism.

A. Chiefly in the belt of weathering.

1. Change to kaolinite, pyrophyllite, halloysite, etc.
2. Change to gibbsite, quartz, and calcite.

B. Chiefly in the belt of cementation.

1. Change to zeolites.
2. Change to prehnite.
3. Change to glauconite.
4. Changes of the belt of weathering, here subordinate.

## II. Alterations due to hot solutions.

## A. Solutions acid.

1. Change to tourmaline, topaz, etc.

## B. Solutions alkaline.

1. Change to sericite, kaolinite, gibbsite, quartz with calcite, albite, adularia, chlorite, etc.

## III. Alterations of the zone of anamorphism.

1. Change to quartz, calcite, and epidote.
2. Change to albite, zoisite, quartz, and muscovite (saussuritization).
3. Change to scapolite.

## IV. Alterations due to heat alone.

Kaolinite forms more frequently from acid than from basic feldspars; it usually forms very small flakes which give the feldspar a cloudy appearance. Further development makes the original mineral opaque. This is probably the ordinary mode of origin of common clay, although the concentration in clay beds is sometimes accomplished by water sorting during transportation. Pyrophyllite is formed much less frequently by weathering. When the process of hydration goes still farther it may result in the formation of halloysite, montmorillonite, or other hydrous aluminum silicates.

Gibbsite may be distinguished from the preceding alteration products by its distinctly oblique extinction in sections normal to the cleavage and by common multiple twinning. It is found especially in basic igneous rocks, affecting particularly the microlitic feldspars of basalt. It is commonly accompanied by secondary quartz and calcite.

Zeolites may result from the alteration of feldspars, especially in basic rocks. The formation of zeolites sometimes seems to involve solution, more or less transportation, and deposition in amygdules. Occasionally the change is indirect; dipyre may form from the feldspar and in turn change to some zeolite. The formation of zeolite may begin in nephelite or a related mineral, and later encroach on a feldspar.

The alteration of feldspar to prehnite resembles the change to zeolites, with which prehnite is often associated. Calcite and quartz may be formed simultaneously.

The alteration to glauconite is found in limestones, in which the clastic grains of orthoclase are sometimes impregnated with lamellae of glauconite which gradually transform the whole grain to an aggregate of very fine green glauconite. This process is now in progress at the bottom of the ocean in some places. Glauconite of the Tertiary limestones is probably in part of the same origin, though the mineral is also produced in large amount through the agency of various kinds of organisms.

Alterations due to hot solutions are common, especially in association with igneous intrusions. Acid solutions, which may be gaseous or liquid, may change feldspars to tourmaline, or to topaz, or to alunite often with native sulfur. Large nearly pure masses of kaolinite seem to have been produced in this way in Cornwall. Alkaline solutions produce effects not so easily recognized, but sometimes feldspars are corroded and then enlarged by a new growth of adularia or albite oriented on the old feldspar; the same or similar conditions may produce sericite, chlorite, quartz, calcite, gibbsite, etc. Mica is especially common as an alteration of feldspar, particularly acid types. The mica is secondary and is therefore called sericite; optically it is characterized usually by a small optic angle, and chemically by water easily expelled. It is sometimes accompanied by secondary gibbsite, quartz, and calcite; in pegmatite, quartz and albite may be accompanying secondary products.

Under anamorphic conditions the alteration of feldspar to a mass of quartz, calcite, and epidote is common. Such alterations are nearly always accompanied or followed by the introduction of iron, chiefly as limonite.

Saussuritization is a process confined to regions where gabbros have suffered dynamic metamorphism. It may be accompanied by the development of a schistosity due to shearing and recrystallization. The plagioclase of the gabbro is transformed by the process into a mass (named *saussurite*) of zoisite, epidote, new acid feldspar, quartz, actinolite, sometimes with garnet and rutile, more rarely with scapolite and calcite. The pyroxene of the gabbros is changed at the same time to green amphibole or to glaucophane.

The alteration of feldspar to scapolite has been studied in great detail in the rocks of the Pyrenees by Lacroix. The special feature of the process is that a single crystal of dipyre may form from a large number of feldspar crystals, thus giving rise to a rock of much coarser texture than its parent. Sometimes this alteration may be due to regional metamorphism and sometimes to hot solutions. It is nearly always accompanied by the uralitization of the pyroxene.

Alterations due to heat alone result in the opening of feldspars along cleavage planes and fractures, and their partial fusion and recrystallization. This process often charges the feldspars with gaseous and vitreous inclusions. It also changes adularia to sanidine; possibly it changes microcline to orthoclase (not yet proved).

It is worthy of note that the same minerals are formed as alteration products under different conditions, outlined above. This is due to the fact that not all the factors producing alteration are stated in a simple classification.

Alteration of feldspar may be followed by regeneration of the same or, more commonly, a more acid type of feldspar. In this way feldspar grains or crystals are sometimes much enlarged. The new feldspar is fresh and glassy, while the old one is more or less permeated with alteration products. The old feldspar may be sanidine and the new one adularia; the old may be calcosodic feldspar and the new pure albite, or even adularia. Such changes occur in all kinds of rocks.

**OCCURRENCE.** The feldspars are the most abundant and most widely distributed minerals of the earth's crust. They serve as the usual basis of classification of the igneous rocks; they are almost as abundant in metamorphic rocks, and even in the sedimentary rocks they are not rare as residual clastic fragments, and are also known as regenerated crystals. They are a normal product of crystallization of all the common types of magmas; they are a common product of metamorphism, both contact and regional; finally, they are often formed in veins from hot solutions, and abundantly in some pegmatite dikes under aqueo-igneous conditions.

**DIAGNOSTICS.** Feldspars are the most abundant colorless constituents of igneous and metamorphic rocks; they are distinguished from quartz by their biaxial character and by the presence of cleavages and common twinning. They are also characterized by low refringence and weak (rarely moderate) birefringence. They alter readily, as already described.

There are many ways of distinguishing between the various kinds of feldspar; these are described below, with special reference to microscopic methods.

1. *Chemical analysis.* Quantitative chemical analysis of pure material is sufficient to determine any feldspar except that it does not distinguish different phases, such as adularia, sanidine, and microcline, nor between anorthoclase and microscopic feldspar intergrowths known as perthite.

2. *Microchemical tests* for various bases (see Part I, page 41) are, in general, only qualitative but may be very helpful in certain cases.

3. *Solubility.* Anorthite and celsian dissolve readily in HCl; bytownite dissolves slowly; all other feldspars are insoluble.

4. *Hardness.* The feldspars do not differ appreciably in hardness.

5. *Specific gravity.* The feldspars vary in specific gravity from 2.54 in potash feldspar to 2.76 in anorthite and 3.4 in celsian.

6. *Cleavage angle.* Monoclinic feldspars (celsian, hyalophane, and orthoclase) may be distinguished from plagioclase by measuring the cleavage angle, which is  $90^\circ$  in the former and about  $94^\circ$  in the latter. The pseudomonoclinic feldspars (microcline and anorthoclase) cannot be distinguished from the monoclinic by such measures.

7. *Twinning.* Monoclinic feldspars have simple twinning (two or rarely three individuals) while pseudomonoclinic and plagioclase feld-



spars commonly show multiple twinning (in one or two sets of bands).

8. *The optic angle* is small in sanidine and anorthoclase; it is large ( $60^{\circ}$ – $90^{\circ}$ ) in all other kinds of feldspar.<sup>66</sup>

9. *The optic sign* is positive in celsian, albite, albitoclase, andesine, and labradorite and negative in other types<sup>67</sup> of feldspar.

10. *Refringence.* The mean index of refraction varies from about 1.52 in adularia to about 1.58 in anorthite and 1.59 in celsian. The indices in various directions can be compared by the methods of normal and

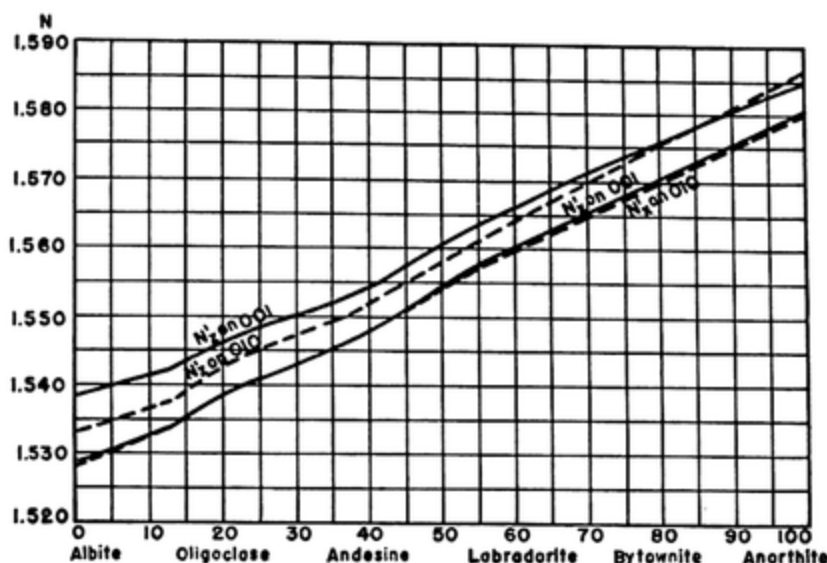


FIG. 173. Indices of refraction on cleavage pieces of plagioclase. [After Tsuboi: *Mineral. Mag.*, XX, 108 (1923).]

inclined illumination (see Part I, pages 76–80) with the index (or indices) of any substance with which the feldspar is in contact. By using the data of Fig. 148 and page 276, the feldspar may usually be accurately identified. In this connection it should be remembered that  $N_0$  of quartz is very constant and available from every quartz grain, and, also, that the index of Canada balsam is not invariable but ranges from 1.534 to 1.540 in good sections free from xylol (a solvent of the balsam). In other sections the range may be as great as from 1.52 to 1.545.

The determination of indices of refraction can be made much more accurate and useful by using mineral powders in various liquids of known index (instead of sections mounted in balsam) as described in Part I, pages 80–82. Since such powders of feldspars consist in large part of 001 and 010 cleavage plates, the indices in these plates are especially important; they have been worked out for plagioclase as shown in Fig.

<sup>66</sup> Andesine and oligoclase with abnormally high tenor of  $K_2O$  have  $2V = 20^{\circ}$ – $50^{\circ}$ . See G. A. Macdonald: *Am. Mineral.*, XXVII, 793 (1942).

<sup>67</sup> Isorthoclase and isomicrocline have positive sign.



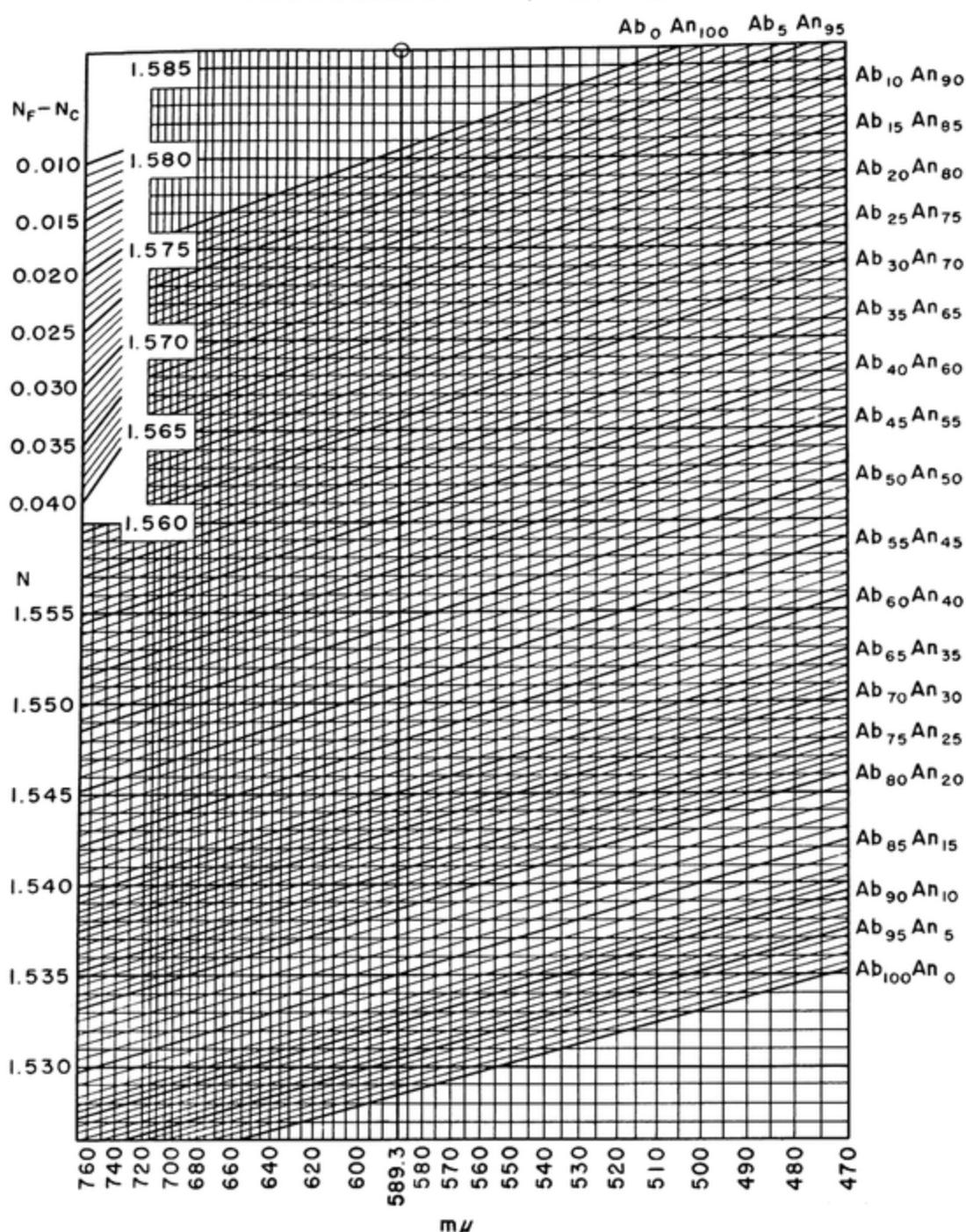


FIG. 174. Lowest index of refraction on cleavage pieces of plagioclase. [After Tsuboi: *Jap. Jour. Geol. Geog.*, XI, 325 (1934).]

173, prepared by Tsuboi.<sup>68</sup> This method of determining plagioclase can be facilitated by plotting the indices for the fast ray ( $N_x'$ ) for all kinds of plagioclase and for all wave lengths of light on a diagram<sup>69</sup> as in Fig. 174 (based on the Hartmann net). It is unnecessary to distin-

<sup>68</sup> S. Tsuboi: *Mineral. Mag.*, XX, 108 (1923).

<sup>69</sup> S. Tsuboi: *Jap. Jour. Geol. Geog.*, XI, 325 (1933-1934).

guish between 001 and 010 cleavage flakes since  $N_X'$  is very nearly the same whichever cleavage is used, as shown in Fig. 173. In order to use this diagram, it is necessary to measure the index of refraction and the dispersion of the immersion liquid which will be used. If the index,  $N_D$ , is 1.553 and the dispersion ( $N_F - N_C$ ) is 0.023, locate  $A$  at 0.023 in the scale at the upper left of Fig. 174 and draw the line  $AB$  connecting this point with the point at the top of the drawing (Fig. 174) marked by the small circle, as shown in Fig. 175. Then draw  $CDE$  parallel to  $AB$  through the point  $D$ , which is the index of refraction of the liquid

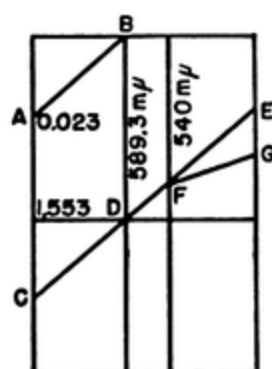


FIG. 175. Use of Fig. 174 in determining plagioclase. [After Tsuboi: *Jap. Jour. Geol. Geog.*, XI, 325 (1934).]

for the Na (D) line. This line  $CDE$  represents the dispersion of the liquid. Next find the wave length at which the index  $N_X'$  of the cleavage flake of plagioclase is the same as the index of the liquid. If this is 540  $m\mu$ , the point  $F$  (at index of the liquid for 540  $m\mu$ ) also gives the index  $N_X'$  of the plagioclase. It is only necessary, then, to follow the dispersion line of the plagioclase ( $FG$ ) to the right side of the diagram to find the composition of the feldspar.

11. *Birefringence.* The birefringence varies from 0.006 in hyalophane and 0.007 in potash feldspar and andesine to 0.011 in celsian and albite and 0.013 in anorthite, as shown on page 276. The birefringence can be determined either by measuring the indices of refraction (and thus getting the difference between  $N_Z$  and  $N_X$ ) or, when studying thin sections, by using Plate I of Part III.

12. *Interference figures from 001 cleavage plates* show the following characters (see Fig. 170, in which 001 is near the center):

In celsian and anorthite an optic axis is at about  $18^\circ$  from the center of the field.

In sanidine the obtuse bisectrix  $Z$  is at about  $6^\circ$  from the center of the field.

In labradorite and bytownite no definite optic direction is in the field.

In other feldspars the optic normal is at  $4^\circ$  to  $20^\circ$  from the center of the field.

13. *Interference figures from 010 cleavage plates* show the following characters, which are very useful if, as assumed in the following statements, it is possible to orient the cleavage plate with the vertical axis running N-S, and the 001 cleavage extending NE-SW:

Celsian and sanidine show a centered optic normal.

Adularia and hyalophane show a centered obtuse bisectrix  $Z$ .

In anorthoclase the obtuse bisectrix  $Z$  is at about  $3^\circ$  from the center of the field.

In microcline the obtuse bisectrix  $Z$  is at about  $12^\circ$  from the center of the field.

In plagioclase (Fig. 171) the bisectrix  $Z$  is about  $15^\circ$  below the center and a little to the right in albite, very near the center in oligoclase, about  $20^\circ$  to the NW of the center in andesine, and outside the field of view in labradorite, bytownite, and anorthite. An optic axis is near the edge of the field to the SW in anorthite.

### EXTINCTION ANGLES

Extinction angles are extremely useful in distinguishing between the various types of feldspar, but they are of no value unless the orientation of the crystal or grain can be learned. Any orientation which is recognizable in any way can be used. See Figs. 215–215e. The most important of these are described in the following paragraphs.

14. *Extinction angles on 001 cleavage plates* are tabulated on page 286 and included in Figs. 148 and 176. Only platy fragments of uniform

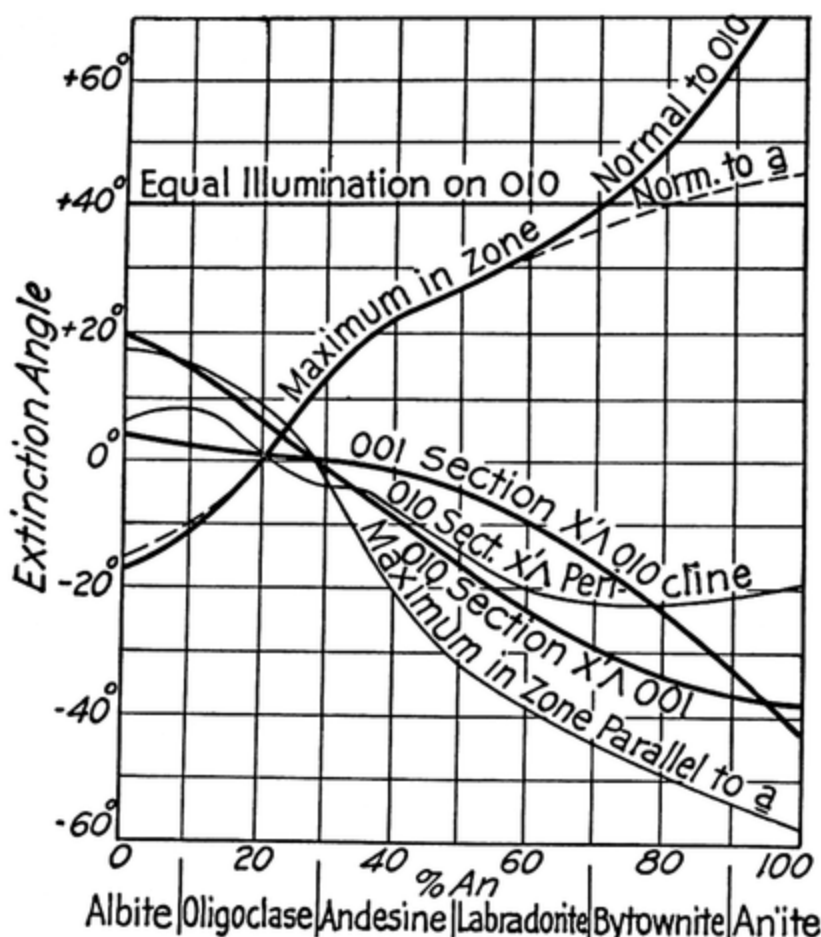


FIG. 176. Extinction angles to  $X'$  in crystallographically oriented sections or cleavage flakes of plagioclase. (After Duparc and Reinhard.)

thickness (and interference color) should be used; further, the 010 cleavage, crystal face, or twinning plane must be found, and the angle between it and the fast ray,  $X'$ , measured. Thin flakes are preferred to avoid the possibility of one crystal being superposed over another in the same flake. Extinction angles on 001 cannot be used in thin sections because crystals cut in the required direction cannot be recognized.

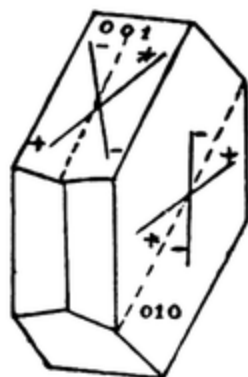
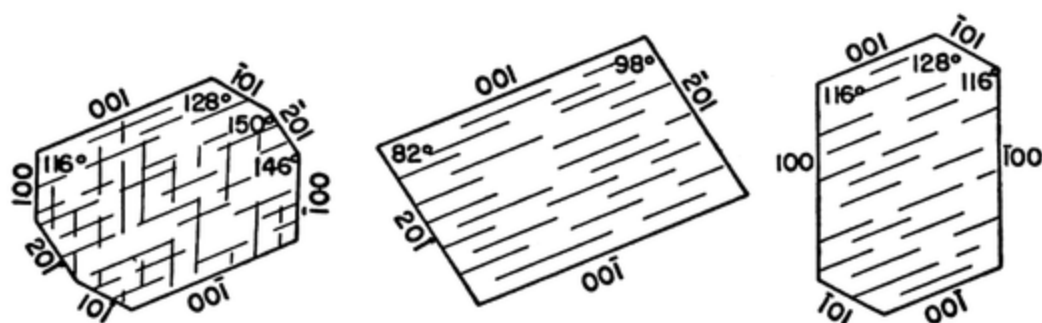


FIG. 177. Schuster's rule for determining the sign of extinction angles in feldspars.

15. *Extinction angles on 010 cleavage plates* are included in the table on page 286 and also in Figs. 148 and 176. Cleavage fragments parallel to 010 are usually smaller and less abundant in a powder than those parallel to 001; they do not show albite twinning bands but are likely to show two opposite parallel edges marking the 001 cleavage.

According to a rule proposed by Schuster, extinction angles on 001 and 010 are considered positive if measured from the cleavage clockwise, and negative if measured anticlockwise, as shown in Fig. 177.

16. *Extinction angles on 010 in thin sections.* Crystals cut parallel with 010 can be recognized in thin sections by the absence of albite twinning (though pericline twinning may be present), by the presence of only one cleavage, and by the crystal form either in outline or in zonal growth with boundaries as shown in Figs. 178–180. In a section 0.02 mm. in thickness, if the section is only approximately parallel with 010 so that two albite twin lamellae overlap through a width of 0.3 mm., the



FIGS. 178–180. Outlines of crystals of feldspar in sections parallel with 010.

section varies less than  $4^\circ$  from parallelism and may be used by allowing a possible error of about  $\pm 2^\circ$  in the results. The 001 cleavage is usually quite distinct and (nearly or exactly) normal to the section; it is seen best by darkening the field or lowering the condenser. Except in celsian, this cleavage is near ( $0^\circ$ – $36^\circ$ ) the extinction direction of the fast ray

( $X'$ ), and also near ( $0^\circ$ – $18^\circ$ ) the pericline twinning plane. Such sections show a perfectly centered interference figure if produced by monoclinic feldspar, and the bisectrix  $Z$  either in the field or nearer than  $X$  (Fig. 171) if produced by triclinic feldspar. Also, such sections may show Carlsbad  $B$  twinning, since this twinning has 100 as its composition face; the 001 basal cleavages make an angle of  $52^\circ$  with each other in the two parts of the twin; extinction angles are equal in the two parts of the twin.

In such twins the angle ( $\omega$ ) between the  $X'$  extinction directions in the two parts of the twin, if the section is parallel with 010, is as follows (see Fig. 181):

Type	% An	$\omega$	$X' \wedge 001$
Albite	0	$168^\circ$	$+20^\circ$
Oligoclase	20	$140^\circ$	$+6^\circ$
Andesine	35	$118^\circ$	$-5^\circ$
Labradorite	52	$94^\circ$	$-17^\circ$
Bytownite	73	$66^\circ$	$-31^\circ$
Anorthite	100	$52^\circ$	$-38^\circ$

In feldspar crystals showing zonal growth the section is parallel with 010 if the angle <sup>70</sup> from 001 (the basal cleavage) to the position of equal illumination of all the zones is  $+40^\circ$ . The zones are especially distinct in such sections, and, since they follow crystal outlines, they may be useful.

When the position of the basal cleavage and that of some face of the vertical zone, such as 110, can be determined, the sign of the extinction angle is given by the rule that positive angles are in the obtuse angle  $\beta$  and negative angles are in the acute angle  $\beta$ . If basal cleavage and Carlsbad twinning are both visible the rule may be applied, since the twinning line, if straight, may be taken as parallel with the axis  $c$ .

17. *Extinction angles in sections normal to  $a$*  are tabulated on page 287 and shown in Fig. 176. Such sections are easily recognized by their nearly square outlines, or by zonal growths with such outlines, and also by the fact that they are at right angles to both cleavages (and to the albite twinning planes) so that these lines are not displaced laterally when the focus is raised or lowered; in such sections albite twins show

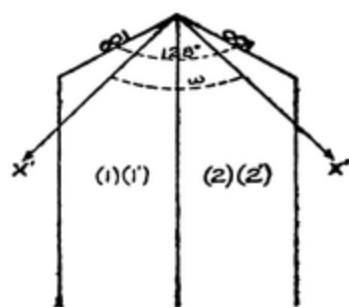


FIG. 181. Carlsbad twinning and crystal outline in a section of feldspar parallel with 010.

<sup>70</sup> This angle is given as  $37^\circ$  by Michel Lévy and as  $40.5^\circ$  by Duparc and Reinhard.

symmetrical extinctions and equal illumination at  $0^\circ$  and  $45^\circ$ . The sign of the extinction angle is given by Schuster's rule. Sections not exactly at right angles to  $a$  can be used by allowing a small margin of error, since the extinction angles do not change rapidly in this region.

EXTINCTION ANGLES OF THE FELDSPARS

Type	On 001	On 010	Section $\perp$ X		Section $\perp$ Z		Sec- tion $\perp$ Y
	X' $\wedge$ 010	X' $\wedge$ 001	Z $\wedge$ 010	Z $\wedge$ 001	X $\wedge$ 010	X $\wedge$ 001	
Celsian	$0^\circ$	$+28^\circ(Z)$	$0^\circ$	$90^\circ$	$0^\circ$	$90^\circ$	$0^\circ$
Hyalophane	$0^\circ$	$-5^\circ-$ $-24^\circ$	$90^\circ$	$0^\circ$		$-5^\circ-$ $-24^\circ$	$0^\circ$
Adularia	$0^\circ$	$+5^\circ$	$90^\circ$	$0^\circ$		$+5^\circ$	$0^\circ$
Sodian adularia	$0^\circ$	$+11^\circ$	$90^\circ$	$0^\circ$		$+11^\circ$	$0^\circ$
Sanidine	$0^\circ$	$+5^\circ$	$90^\circ$	$0^\circ$	$0^\circ$	$90^\circ$	$+5^\circ$
Microcline	$+10^\circ-$ $+15^\circ$	$+5^\circ$	$88^\circ$	$2^\circ$		$+10^\circ$	$+15^\circ$
Anorthoclase	$+2^\circ$	$+4^\circ-$ $+10^\circ$	$89^\circ$	$1^\circ$		$+9^\circ\pm$	$+1^\circ-$ $+4^\circ$
Plagioclase							
Albite, Ab <sub>100</sub> An <sub>0</sub>	$+4^\circ$	$+20^\circ$	$+74^\circ$	$+13^\circ$	$+2^\circ$	$+21^\circ$	$+1^\circ$
Oligoclase, Ab <sub>75</sub> An <sub>25</sub>	$+1^\circ$	$+4^\circ$	$-84^\circ$	$-9^\circ$	$-3^\circ$	$+3^\circ$	$0^\circ$
Andesine, Ab <sub>55</sub> An <sub>45</sub>	$-4^\circ$	$-12^\circ$	$-73^\circ$	$-31^\circ$	$-22^\circ$	$-18^\circ$	$-8^\circ$
Labradorite, Ab <sub>45</sub> An <sub>55</sub>	$-7^\circ$	$-18^\circ$	$-63^\circ$	$-40^\circ$	$-28^\circ$	$-30^\circ$	$-15^\circ$
Bytownite, Ab <sub>25</sub> An <sub>75</sub>	$-17^\circ$	$-31^\circ$	$-58^\circ$	$-55^\circ$	$-40^\circ$	$-49^\circ$	$-28^\circ$
Anorthite, Ab <sub>0</sub> An <sub>100</sub>	$-40^\circ$	$-38^\circ$	$-59^\circ$	$-73^\circ$	$-62^\circ$	$-64^\circ$	$-41^\circ$

18. *Extinction angles in the zone parallel with  $a$*  are given on page 287 and also in Fig. 176. A single measure is not sufficient, since it is necessary to find the maximum extinction angle of the zone. The microclites of volcanic rocks are elongated parallel to  $a$  and may be too small to show twinning; in such cases this method may be made to give good results (if the maximum angle attains  $12^\circ$ ) by using the index of refraction to distinguish between albite and andesine.



## EXTINCTION ANGLES OF THE FELDSPARS

Type	Zone $\perp 010$	Zone $\parallel a$	Sec- tion $\perp a$	Section $\perp A$		Section $\perp B$	
	Max. = Angle	Max. Angle		Angle Measured		From Optic Plane	
	$X' \wedge$ 010	Micro- lites		To 010	To 001	To 010	To 001
Celsian	0°	+28°	0°	0°	90°	0°	90°
Hyalophane	0°	+5°- +24°	0°	90°	-2°- -10°±	90°	-2°- -10°±
Adularia	0°	+5°±	0°	90°	+2°±	90°	+2°±
Anorthoclase	2°	+9°±	+1°?	90°	+4°±	90°	+4°±
Microcline	+19°	+16°	+4°	90°	+2°±	90°	+2°±
Plagioclase							
Albite, $Ab_{100}An_0$	-20°	+17°	-15°	+66°	-22°	+65°	+7.5°
Oligoclase							
$Ab_{75}An_{25}$	+6°	+5°	+7°	-82°	+6°	-81°	+9°
Andesine							
$Ab_{55}An_{45}$	+25°	-27°	+25°	-56°	+25.5°	-59°	+16°
Labradorite							
$Ab_{45}An_{55}$	+30°	-38°	+32°	-43°	+41°	-61°	+1°
Bytownite							
$Ab_{25}An_{75}$	+42°	-47°	+40°	-31°±	+54°?	-61°±	+1°?
Anorthite							
$Ab_5An_{95}$	+56°	-57°	+44°	-22°±	+63°?	-61°±	+4°?

19. *Extinction angles in the zone normal to 010* are tabulated on page 287 and included in Figs. 148 and 176. Half a dozen measures usually suffice to obtain a value close enough to the maximum. Sections normal to 010 can be recognized, if albite twinning is present, by the following characters: (1) the twinning line bisects the angle between extinction positions of two adjacent twinning bands; (2) twinning planes and cleavages do not move laterally when the focus (high power) is raised or lowered through the thickness of the section; (3) the twinned parts show equal illumination eight times in a complete rotation, namely, four times when the twinning line is parallel with a cross hair and *also four times at 45°* from the cross hairs. In these positions the lamellae appear to belong to a single crystal, being separated only by a very narrow dark

line, sometimes almost invisible. This test is extremely delicate and easily applied. Sections varying up to  $10^\circ$  or  $15^\circ$  from the true zone may still be used by averaging the values of the extinction angles. That is, if the extinction angles do not differ more than  $2^\circ$  or  $3^\circ$  (or, with large angles, more than 10 per cent) the average value is sufficiently accurate. The angle should always be measured from the fast ray ( $X'$ ) to the albite twinning line (or the 010 cleavage). The sign of the extinction angle is nearly always unknown; therefore the method does not distinguish between albite and andesine, but they may be distinguished by the index of refraction method.

Determination of the feldspars by means of the extinction angles in the zone normal to 010 is somewhat tedious because the *maximum* angle of the zone must be found, but it is reliable and serviceable because of the readiness with which sections normal to 010 can be recognized and also because there are decided differences in the maxima of the different feldspars. The chief objections to the method are due to (1) the possible existence of two or more feldspars in the same rock, and (2) the possible absence of the section showing the maximum equal extinction angle in any of the crystals of the random rock section. However, the second difficulty is not serious unless the section cuts only a few crystals of feldspar, and the obvious remedy is to secure more sections. The first difficulty is more serious and is only partly obviated by the fact that when two feldspars are present in one rock they *may* differ in transparency, or mode of distribution, or other evident characters.

20. *Extinction angles in albite-Carlsbad twins cut normal to 010.* If any section normal to 010 is twinned both on the albite and the Carlsbad laws, a single section is sufficient to identify the feldspar, and it is unnecessary to hunt for the maximum equal extinction angle of the zone. Such crystals may be recognized by the fact that at the  $45^\circ$  position the albite twinning disappears and the crystal seems to be a simple Carlsbad twin, whereas at the  $0^\circ$  position both the albite and the Carlsbad twinning disappear, except for fine dark lines due to slight overlapping of the albite twinning lamellae. Such sections give equal extinction angles in the albite lamellae in each part of the Carlsbad twin, thus giving two pairs of equal angles. In Fig. 148 the horizontal lines express the value of the smaller equal extinction angles, and the curves ("Albite-Carlsbad twinning") express the value of the larger equal extinction angles. The vertical lines give the percentage of anorthite. In using these curves there is no possible ambiguity except when both pairs of equal extinction angles are  $16^\circ$  or less; then if the two parts of the Carlsbad twin show practically no difference in birefringence at the  $45^\circ$  position the plagioclase is more acid than oligoclase ( $Ab_5An_1$ ), and if a distinct difference

appears (0.003 or more), the plagioclase is more basic than oligoclase. Sections inclined as much as  $10^\circ$  from the zone normal to 010 may be used with approximate accuracy by adopting the averages of the unequal extinction angles as equivalent to the equal angles that would be obtained if the orientation were correct.

21. *Extinction angles in zoned albite twins cut normal to 010.* If a section normal to 010 shows zonal growth as well as albite twinning, a

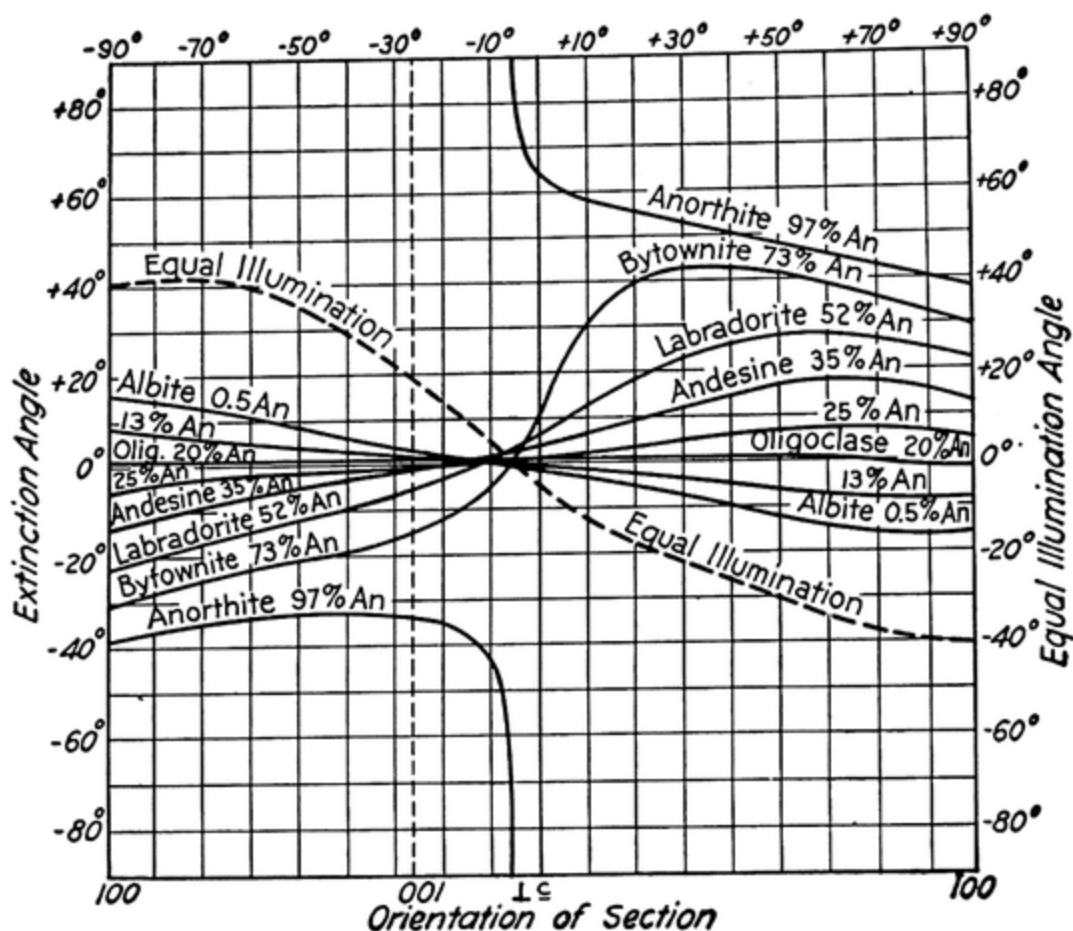


FIG. 182. Extinction angles to  $X'$  in sections of plagioclase normal to 010 with both albite twinning and zonal growths. (Modified from Duparc and Reinhard.)

single section is sufficient to identify the feldspar by the aid of Fig. 182. It is necessary only to measure the smallest angle from 010 to a position of equal illumination of all the zones, find the corresponding point on the diagram, and from that point follow the ordinate to a point on (or between) the extinction angle curves which represents the extinction angle ( $X' \wedge 010$ ) in the given section; if the position of equal illumination and the extinction position are measured in the same direction from 010, the corresponding points on the diagram are on the same (right or left) half of the diagram; if not, they are on opposite sides of the diagram.

Unfortunately, a given angle to a position of equal illumination can be found on either side of the diagram, so there are commonly two possible answers; some other method must be used to enable one to choose correctly between these two answers.

22. *Extinction angles in sections normal to an optic axis* are not often useful for three reasons: (1) it is often impossible to distinguish between the two optic axes;<sup>71</sup> (2) such sections are nearly at extinction in all positions, and therefore the correct position of extinction is very difficult to recognize—however, the angle should be measured from the trace of the optic plane which can be located easily by means of the interference figure; and (3) extinction angles in this region vary rapidly so that only sections very accurately oriented (with the optic axis exactly in the middle of the interference figure) can be used. However, in spite of these difficulties such sections deserve attention because they are easily recognized by their extremely weak birefringence. The second objection really becomes an advantage because the "extinction position" can be obtained accurately by making the isogyre parallel with one cross hair. In a section normal to either optic axis, an extinction angle (optic plane to 010) less than  $45^\circ$  means that the feldspar is more basic than andesine, and an angle greater than  $68^\circ$  means that the feldspar is oligoclase. Extinction angles between  $45^\circ$  and  $68^\circ$  are ambiguous except that an angle of about  $53^\circ$  is distinctive of labradorite. Finally, sections normal to an optic axis are especially useful if they form part of a twin, since the extinction angles in the other part of such sections of twinned crystals are known (see page 294 and Figs. 183 and 184). In these crystals extinction angles are measured from the twinning line to the position of the optic plane. If they are twinned the extinction angles in other parts of the twin are measured from the vibration direction of the fast ray,  $X'$ . The sign of the extinction angle (given by Schuster's rule) is very rarely determinable in practice. If the crystal concerned is twinned on the pericline law, the extinction angles, meas-

<sup>71</sup> But if both cleavage directions can be found the angle between them serves to distinguish A from B, except in oligoclase, by use of the following data:

ANGLES BETWEEN CLEAVAGES ( $001 \wedge 010$ ) IN SECTIONS NORMAL TO OPTIC AXES

Section	Ab <sub>100</sub> An <sub>0</sub>	Ab <sub>75</sub> An <sub>25</sub>	Ab <sub>55</sub> An <sub>45</sub>	Ab <sub>45</sub> An <sub>55</sub>	Ab <sub>25</sub> An <sub>75</sub>	Ab <sub>0</sub> An <sub>100</sub>
⊥ A	88°	88°	81.5°	84°	85°	85°
⊥ B	57.5°	90°	75°	62°	62°?	64°?

Also, the optic plane turns perceptibly in succeeding zones in sections normal to A, while it does not turn (though B moves in a plane normal to the optic plane) in sections normal to B, according to Becke.

ured from the twinning line to the trace of the optic plane, are given for both parts of the twin on page 294.

23. *Extinction angles in sections normal to Y, or parallel to the optic*

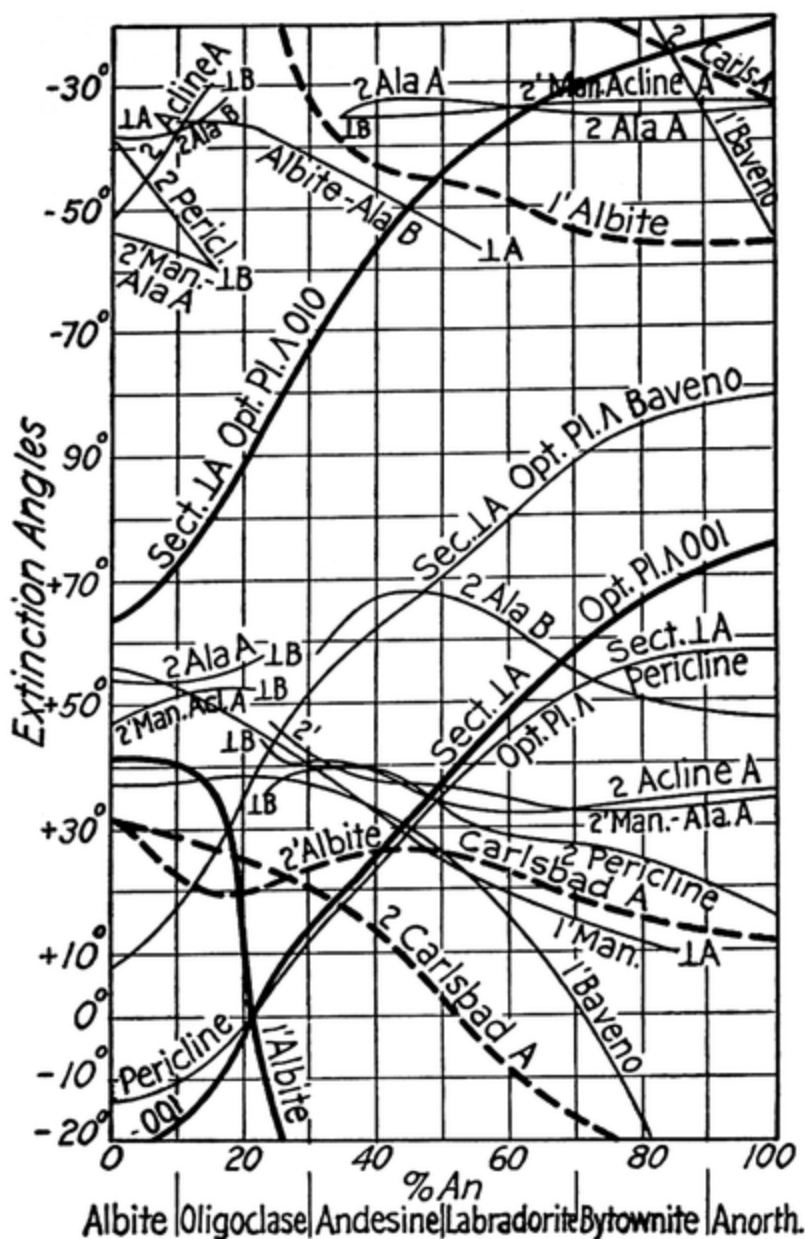


FIG. 183. Extinction angles to  $X'$  in sections of plagioclase normal to the optic axis A and in parts twinned therewith on various laws. (Modified from Duparc and Reinhard.)

plane, are tabulated on pages 286 and 294, and included in the graphs of Figs. 148 and 185 and also in Figs. 215–215e. Such sections are easily recognized by the fact that they show the highest interference color given by any crystal of the feldspar and also (more accurately) by the







EXTINCTION ANGLES NORMAL TO A, B, AND Y IN PLAGIOCLASE <sup>72</sup>

Name	Section ⊥ A (1) Optic Plane ∧ 010	(1')	(2)	(2')	Section ⊥ B (1) Optic Plane ∧ 010	(1')	(2)	(2')	Section ⊥ Y (1) X ∧ 010	(1')
Albite (Ab <sub>100</sub> An <sub>0</sub> )	+66°	+37°	+30°	+28°	+65°	+40°	+45°	−32°	+1°	
Oligoclase (Ab <sub>80</sub> An <sub>20</sub> )	90°	0°	+25°	+25°	90°	90°	−35°	−25°	+1°	
Oligoclase (Ab <sub>75</sub> An <sub>25</sub> )	−82°	−40°	+22°	+22°	−81°	−42°	−17°	−16°	0°	
Andesine (Ab <sub>60</sub> An <sub>40</sub> )	−63°	−48°	+15°	+35°	−59°	−31°	−6°	0°	−3.5°	3°
Labradorite (Ab <sub>50</sub> An <sub>50</sub> )	−47°	−40°	+10°	+27°	−57°	−23°	+3°	+14°	−13°	12°
Anorthite (Ab <sub>0</sub> An <sub>100</sub> )	−20°	−53°	−25°	+15°	−62°	−12°	+47°	−56°	−41°	38°
	Albite twin		Albite twin		Albite twin		Albite twin		Albite twin	
	Carlsbad twin				Carlsbad twin					

## EXTINCTION ANGLES ON PERICLINE TWINNING IN PLAGIOCLASE

Name	Section ⊥ A (1)	(1')	Section ⊥ B (1)	(1')	Section ⊥ X (1)	(1')	Section ⊥ Y (1)	(1')	Section ⊥ Z (1)	(1')
Albite (Ab <sub>100</sub> An <sub>0</sub> )	+5.5°	+41°	-10.5°	-35.5°	+77°	-76°	-13°	-16.5°	-3°	-1°
Oligoclase (Ab <sub>80</sub> An <sub>20</sub> )	-4.5°	-61°	0°	+30°	-86.5°	+89.5°			-3°	-3.5°
Oligoclase (Ab <sub>75</sub> An <sub>25</sub> )	-10.5°	-43.5°	+4°	+49.5°	-75.5°	+85°			-4.5°	-4°
Andesine (Ab <sub>62.5</sub> An <sub>37.5</sub> )	-20°	-35°	+12.5°	+42.5°	-68.5°	+69°	-17°	-25°	-6.5°	-1.5°
Labradorite (Ab <sub>50</sub> An <sub>50</sub> )	-25.5°	-23.5°	+19.5°	+66°	-57.5°	+57°	-12°	-34°	-8°	+7.5°
Labradorite (Ab <sub>43</sub> An <sub>57</sub> )	-38°	-17°	+15.5°	+49.5°	-49.5°	+42°	-20°	-68°	-17.5°	+12°
Anorthite (Ab <sub>0</sub> An <sub>100</sub> )	-57°	-17°	-35°	+13°	-34.5°	+21°	-24.5°	+76.5°	-33.5°	+19.5°
	Pericline twin		Pericline twin		Pericline twin		Pericline twin		Pericline twin	

<sup>72</sup> F. Becke: *Tsch. Min. Pet. Mit.*, XXXV, 31 (1921), and G. Cesàro: *Bull. Soc. Fr. Min.*, XXXIX, 57 (1916), who gives for bytownite ⊥ Y an angle of 30°, and in the part albite-twinned with it an angle of 28°.

trace of the optic plane to 001 in acid plagioclases, and to 010 in basic plagioclases; but, if either happens to be invisible, the other may be used and the percentage of anorthite determined by reference to the

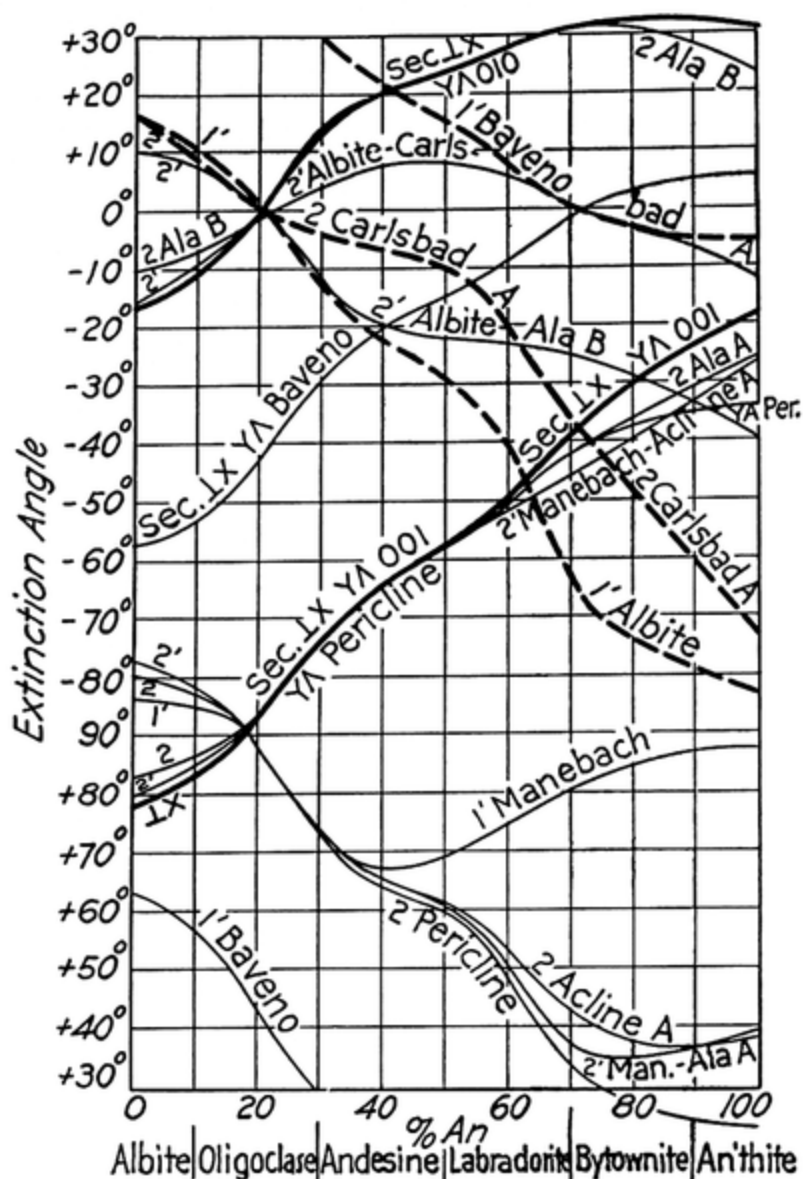


FIG. 186. Extinction angles to  $X'$  in sections of plagioclase normal to the bisectrix  $X$  and in parts twinned therewith on various laws. (Modified from Duparc and Reinhard.)

proper curve of Fig. 148 or Fig. 187. Rarely, neither cleavage nor albite twinning can be seen, but a different kind of twinning is visible. If this is multiple it must be the pericline or the accline type, and the data on page 294 then give the determination needed. Extinction angles to various kinds of twinning for sections normal to a bisectrix are shown in



to adularia (hyalophane) and to sanidine.<sup>73</sup> X-ray studies suggest that barium feldspar can be pseudomonoclinic,<sup>59</sup> and a triclinic phase may be inferred from the description of kasoite<sup>74</sup> [near  $Cn_{50}(Or,Ab)_{50}$ ], since it is said to have an extinction angle of  $10^\circ$ – $13^\circ$  on 001.

Potassium feldspar ( $KAlSi_3O_8$ ) exists in three (or even four?) crystal phases, but the relations between these are not yet understood. Ordinary orthoclase of plutonic rocks has properties which differ a little from those of adularia,<sup>75</sup> but perhaps these two are one phase. This low-temperature phase differs notably from the high-temperature phase, called sanidine, though both are monoclinic. Adularia changes to sanidine on heating to about  $900^\circ$  according to Merwin,<sup>76</sup> but the temperature of change varies, reaching  $1100^\circ$  in many crystals,<sup>75</sup> and is very sluggish. The reverse change does not take place easily but may occur with very slow cooling. Still another phase of  $KAlSi_3O_8$  is pseudomonoclinic and triclinic; it is known as microcline. Some writers have argued that orthoclase and microcline differ only in the coarseness of their twinning, which is visible microscopically in microcline and supposed to be present (but invisible) in orthoclase. However, the most accurate measures of specific gravity, optic axial angle, and refractive indices seem to indicate real, though slight, differences between orthoclase and microcline, and the fact that orthoclase inverts at about  $1100^\circ$  while microcline is stable to its melting point seems to show that the two are not identical. According to Alling,<sup>77</sup> shearing stresses at low temperature tend to cause orthoclase to change to microcline, but this needs further proof.

Sodium feldspar ( $NaAlSi_3O_8$ ) exists in nature in the triclinic phase known as albite, but this inverts<sup>76</sup> at about  $900^\circ$  to a different modification whose properties have not been determined. Furthermore,  $NaAlSi_3O_8$  is miscible<sup>78</sup> at high temperature, probably in all proportions, with sanidine; and it is therefore probable that the high-temperature phase is monoclinic. Such a phase has been named barbierite by Schaller.<sup>79</sup> Again, nearly pure  $NaAlSi_3O_8$  (with as little as 10%  $KAlSi_3O_8$ ) crystallizes in a pseudomonoclinic form called anorthoclase; the name analbite<sup>80</sup> has been suggested for the sodium end-member of this series.

<sup>73</sup> E. S. Larsen *et al.*: *Bull. Geol. Soc. Am.*, LII, 1841 (1941).

<sup>74</sup> T. Yoshimura: *Jour. Geol. Soc. Japan*, XLIII, 877 (1936).

<sup>75</sup> E. Spencer: *Min. Mag.*, XXIV, 453 (1937).

<sup>76</sup> H. E. Merwin: *Jour. Wash. Acad. Sci.*, I, 59 (1911).

<sup>77</sup> H. L. Alling: *Jour. Geol.*, XXIX, 209, 275, and 292 (1921).

<sup>78</sup> E. Mäkinen: *Geol. För. Förh. Stockholm*, XXXIX, 121 (1917).

<sup>79</sup> W. T. Schaller: *Am. Jour. Sci.*, CLXXX, 358 (1910); *Jour. Wash. Acad. Sci.*, I, 114 (1911); and *U. S. Geol. Surv. Bull.* 509, 40 (1912).

<sup>80</sup> A. N. Winchell: *Jour. Geol.*, XXXIII, 714 (1925).

Calcium feldspar ( $\text{CaAl}_2\text{Si}_2\text{O}_8$ ) has only one crystal phase (so far as known), which is the triclinic anorthite.

Barium feldspar and calcium feldspar are miscible only in very small amounts. Less than 1% CaO has ever been found in celsian, and less than 1% BaO has ever been found in anorthite.

Barium feldspar and sodium feldspar are only a little more miscible than barium feldspar and calcium feldspar.

Barium feldspar was supposed to form a continuous isomorphous series with potassium feldspar, and it is clear that barium feldspar can

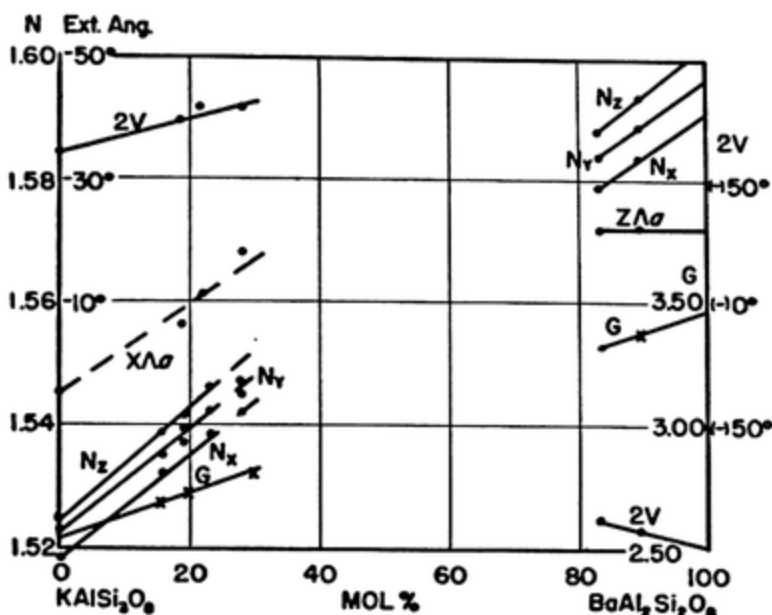


FIG. 188. Properties of the adularia-celsian discontinuous series.

enter the crystal structure of adularia to at least 30 per cent as found in hyalophane; but a continuous series now seems very improbable, since feldspar near  $\text{Cn}_{50}(\text{Or},\text{Ab})_{50}$  in composition<sup>74</sup> is said to have an extinction angle of 10°–13° on 001, which would indicate that it is triclinic. The properties of the discontinuous series are shown approximately in Fig. 188.

Potassium feldspar has complicated relations with sodium feldspar. As already noted, a high-temperature phase of  $\text{NaAlSi}_3\text{O}_8$  is miscible probably in all proportions with the high-temperature phase of  $\text{KAlSi}_3\text{O}_8$ , thus forming the sanidine-barbierite series. Adularia (low-temperature  $\text{KAlSi}_3\text{O}_8$ ) is monoclinic and forms a discontinuous series with triclinic albite. The discontinuity seems to extend from about  $\text{Or}_{50}\text{Ab}_{50}$  to about  $\text{Or}_{10}\text{Ab}_{90}$ . Pseudomonoclinic  $\text{KAlSi}_3\text{O}_8$  (microcline) seems to form a discontinuous series with pseudomonoclinic analbite (which may be continuous under favorable conditions), the discontinuity extending from about  $\text{Or}_{80}\text{Ab}_{20}$  to about  $\text{Or}_{40}\text{Ab}_{60}$ . Members of this



series from about  $Or_{40}Ab_{60}$  to  $Or_{10}Ab_{90}$  are called anorthoclase—they are only metastable at ordinary temperature.

Sanidine-barbierite mix-crystals may separate on cooling to form an aggregate of two feldspars, known as perthite. The sodium feldspar of perthite is much like albite but may not have albite twinning. Sanidine-barbierite mix-crystals of composition between  $Or_{100}$  and  $Or_{70}Ab_{30}$  are metastable at ordinary temperature; those between  $Or_{70}Ab_{30}$  and about  $Or_{10}Ab_{90}$  are unstable and usually change to perthitic aggregates; those between  $Or_{10}Ab_{90}$  and  $Ab_{100}$  change to albite.

Sometimes similar aggregates are composed of microcline and albite (without albite twinning); they are then called microcline-perthite.

Some of these relationships are shown in Fig. 189, in which the break between the adularia-albite series and the microcline-analbite series is

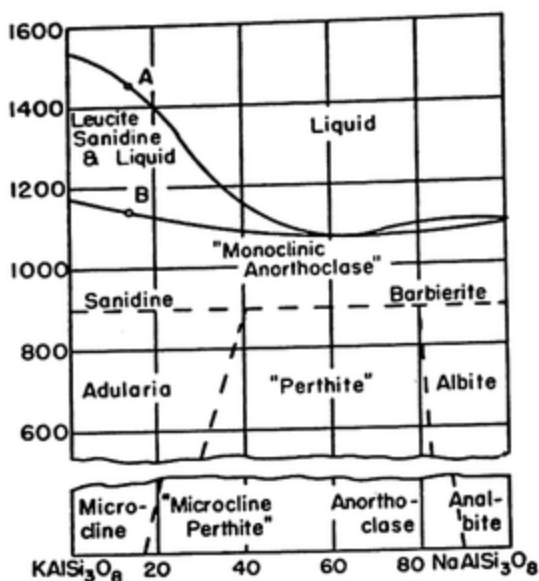


FIG. 189. Stability relations in the potash-soda series of feldspars.

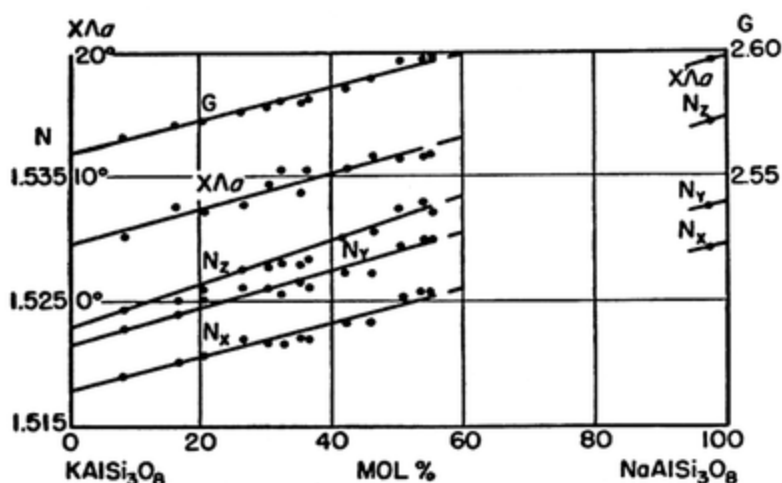


FIG. 190. Properties of the adularia-albite discontinuous series. See E. Spencer: *Mineral. Mag.*, XXII, 306 (1930), and XXIV, 453 (1937).

not intended to indicate any definite temperature, since pressure or shearing may be more important than temperature.

The relations between optic properties and composition in the adularia-albite series are shown in Fig. 190, which is based on better data than Fig. 189 but is, nevertheless, only an approximation.

The probable relationships between optic properties and composition in the sanidine-barbierite series are shown in Fig. 191, which is unfortunately based on very scanty and unsatisfactory data.

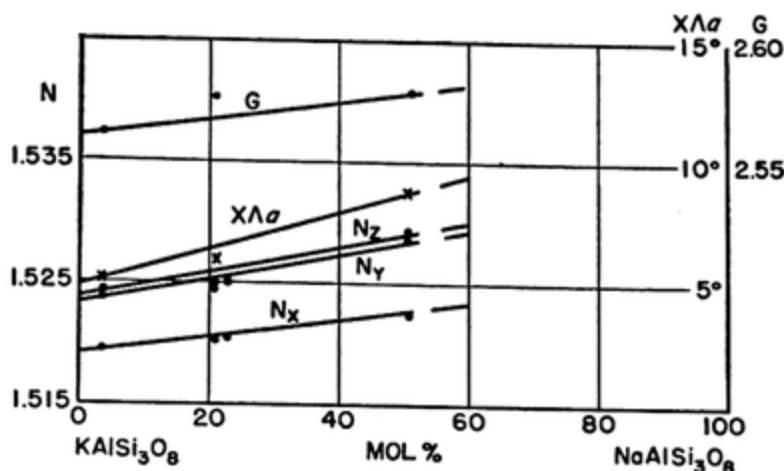


FIG. 191. Properties of the sanidine-barbierite (discontinuous?) series.

The relations between optic properties and composition in the microcline-analbite series are shown in Fig. 192, for which the data are not

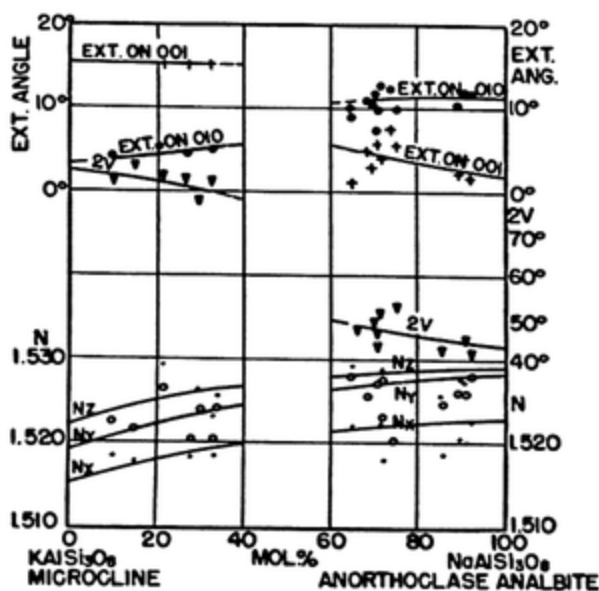


FIG. 192. Properties of the microcline-analbite (discontinuous?) series.

much better than for Fig. 191 though the properties of microcline are known fairly well.

The sodium and calcium feldspars are miscible in all proportions in triclinic crystals which are stable under a wide range of conditions; they

form a continuous series<sup>81</sup> known as plagioclase, from albite ( $\text{NaAlSi}_3\text{O}_8$ ) to anorthite ( $\text{CaAl}_2\text{Si}_2\text{O}_8$ ). Intermediate mix-crystals have long been known as oligoclase, andesine, labradorite, or bytownite, depending upon the ratio of albite to anorthite present; but there is no agreement as to the precise definitions of these names. The usages of various authorities are shown diagrammatically in Fig. 193, together with a modification suggested by the author.

Those who study minerals are accustomed to regard them as (elements or) compounds of definite chemical composition corresponding with some

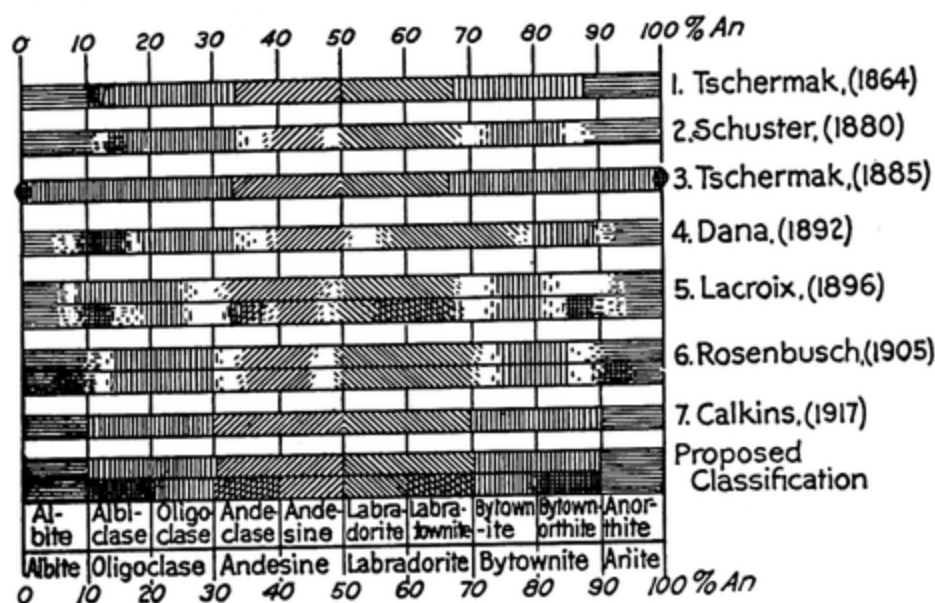


FIG. 193. Classifications of plagioclase.

simple chemical formulas; therefore, even after the gradual acceptance of Tschermak's idea that albite and anorthite are miscible in all proportions in plagioclase, mineralogists have thought and written of triclinic feldspars in terms of various definite mixtures of the end compounds in simple ratios. This fact is responsible for much of the confusion regarding the classification of various kinds of plagioclase. Such a practice is clearly not in harmony with the facts of nature (see Fig. 149), since

<sup>81</sup> W. H. Taylor, J. A. Darbyshire, and H. Strunz (*Zeit. Krist.*, LXXXVII, 464, 1934) found that  $c$  in anorthite is twice as long as  $c$  in albite with a change at about  $\text{Ab}_{50}\text{An}_{50}$ , but S. H. Chao and W. H. Taylor (*Proc. Roy. Soc. London A*, CLXXVI, 76, 1940) show that this change is probably achieved gradually in the sense that it is accomplished by varying the ratio between albite sheets and anorthite sheets. In spite of this evidence that the plagioclase series includes two minerals it will be described here as one because all the properties (except the value of  $c$ ) show continuous variation.

it implies that the usual plagioclase crystal is composed of albite and anorthite in some simple ratio, whereas actual analyses show that simple ratios are mere accidents, and all possible ratios exist. Accordingly it seems better to use simple (decimal) ratios not as characteristic of types but as arbitrary and artificial limits of types.

There has been a decided tendency to use compound names like oligoclase-albite to designate more exactly the kinds of plagioclase found in various cases. This tendency began near the start of the century in the writings of Schuster and is well developed in the works of Lacroix,<sup>82</sup> who employs five such names. The plan presented in Fig. 193 includes abbreviated forms of such names and gives them precise meanings.

The feldspars may be classified as follows:

#### MONOCLINIC FELDSPARS

Orthoclase (Adularia)	$\text{KAlSi}_3\text{O}_8$ (= Or)
Barian adularia (Hyalophane)	(Or, Cn)
Sodian adularia	(Or, Ab)
Sanidine	$\text{KAlSi}_3\text{O}_8$ (= Or)
Barian sanidine	(Or, Cn)
Sodian sanidine	(Or, Ab)
Barbierite	$\text{NaAlSi}_3\text{O}_8$
Celsian	$\text{BaAl}_2\text{Si}_2\text{O}_8$

#### PSEUDOMONOCLINIC (TRICLINIC) FELDSPARS

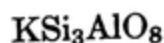
Microcline	$\text{KAlSi}_3\text{O}_8$
Sodian microcline	(Or, Ab)
Anorthoclase	(Ab, Or)
Analbite	$\text{NaAlSi}_3\text{O}_8$ (hypothetical)

#### TRICLINIC FELDSPAR

Plagioclase	Albite <sup>83</sup>	( $\text{NaAlSi}_3\text{O}_8$ = Ab)	Ab <sub>100</sub> An <sub>0</sub> to Ab <sub>90</sub> An <sub>10</sub>
	Oligoclase	{ Albicase	Ab <sub>90</sub> An <sub>10</sub> to Ab <sub>80</sub> An <sub>20</sub>
		{ Oligoclase	Ab <sub>80</sub> An <sub>20</sub> to Ab <sub>70</sub> An <sub>30</sub>
	Andesine	{ Andecase	Ab <sub>70</sub> An <sub>30</sub> to Ab <sub>60</sub> An <sub>40</sub>
		{ Andesine	Ab <sub>60</sub> An <sub>40</sub> to Ab <sub>50</sub> An <sub>50</sub>
	Labradorite	{ Labradorite	Ab <sub>50</sub> An <sub>50</sub> to Ab <sub>40</sub> An <sub>60</sub>
		{ Labratownite	Ab <sub>40</sub> An <sub>60</sub> to Ab <sub>30</sub> An <sub>70</sub>
	Bytownite	{ Bytownite	Ab <sub>30</sub> An <sub>70</sub> to Ab <sub>20</sub> An <sub>80</sub>
		{ Bytownorthite	Ab <sub>20</sub> An <sub>80</sub> to Ab <sub>10</sub> An <sub>90</sub>
	Anorthite <sup>83</sup>	( $\text{CaAl}_2\text{Si}_2\text{O}_8$ = An)	Ab <sub>10</sub> An <sub>90</sub> to Ab <sub>0</sub> An <sub>100</sub>

<sup>82</sup> A. Lacroix: *Minéral. France*, II, 130 (1896).

<sup>83</sup> Johannsen has proposed (*Jour. Geol.*, XXXIV, 840, 1926) using the terms *sodacase* and *calcicase* for the two end portions of the plagioclase series, reserving the names albite and anorthite to designate the pure molecules; albite and anorthite would then be *minerals* in the sense proposed by Alling (*Jour. Geol.*, XXXIV, 591, 1926).

**ORTHOCLASE**<sup>84</sup> (*Adularia*) MONOCLINIC PRISMATIC

$$a:b:c = 0.654:1:0.554 \quad \beta = 116^\circ$$

**COMP.** Orthoclase varies in composition from the (nearly) pure compound to crystals with as much as 30%  $NaAlSi_3O_8$ , or up to 30%  $BaAl_2Si_2O_8$  (*hyalophane*), or it may contain small amounts of other molecules, such as  $CaAl_2Si_2O_8$ ,  $RbAlSi_3O_8$ , etc. In rare cases<sup>85</sup> it may contain up to about 10%  $KFeSi_3O_8$ . Orthoclase (probably metastable) containing up to 50%  $NaAlSi_3O_8$  is known.

**STRUC.** Space group<sup>59</sup>  $C2/m$ ;  $a$  8.45,  $b$  12.9,  $c$  7.15 (but decreasing some with increase of Na). U.C. 4.

**PHYS. CHAR.** Crystals often short prismatic with  $\{110\}$ ,  $\{001\}$ , and  $\{\bar{1}01\}$ . Carlsbad twinning common; Baveno and Manebach twinning uncommon. See Fig. 194. Perfect 001 and distinct 010 cleavages. Fusion of pure  $KAlSi_3O_8$  with formation of leucite begins<sup>75</sup> at  $1170^\circ$ ; it is complete at  $1530^\circ$ . See Fig. 189.  $H. = 6$ .  $G. = 2.57$ .

**OPT. PROP.** The optic plane and  $Z$  are normal to 010, and the acute bisectrix  $X$  makes an angle of about  $5^\circ$  (to about  $11^\circ$  with more Na; see Fig. 197) with  $a$  (the trace of the basal cleavage) in 010. Distinct horizontal dispersion with  $r > v$ . Optic sign negative. Optic angle large (usually about  $50^\circ$  to  $70^\circ$  in "adularia" and  $60^\circ$  to  $85^\circ$  in orthoclase. See Figs. 195 and 196.  $N_X = 1.519$ – $1.526$ ,  $N_Y = 1.523$ – $1.530$ ,  $N_Z = 1.524$ – $1.533$ ,  $N_Z - N_X = 0.005$ – $0.007$ .

The refringence, birefringence, extinction angle, and specific gravity increase with increase in sodium (see Fig. 190). When orthoclase is heated the optic angle decreases at about  $73^\circ$  ( $900^\circ$  to)  $1150^\circ$ , becoming  $0^\circ$  and opening in 010 at right angles to the previous position. This doubtless marks the inversion to the high-temperature phase (sanidine). If the temperature does not reach  $600^\circ$  ca., the final condition (after

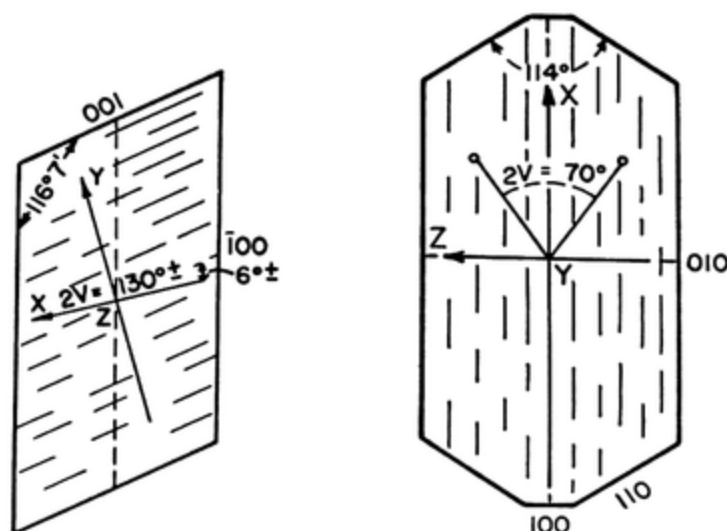
<sup>84</sup> As commonly used, orthoclase is the name of any monoclinic potassium feldspar (including sanidine); more accurately, such feldspar of volcanic rocks is usually sanidine, that of plutonic rocks is orthoclase, that of pegmatites (and veins) is usually adularia, and a lamellar type found in veins is sometimes called valencianite.

<sup>85</sup> G. J. Faust: *Am. Mineral.*, XXI, 735 (1936).



FIG. 194. Photomicrograph of adularia in thin section showing Carlsbad and Baveno twinning.

cooling) is about the same as at first. If inversion occurs, the change is not easily reversed, and the high-temperature phase may persist with little change on cooling. In this way the optic angle may be changed to almost any value in the plane normal to 010 and up to about  $20^\circ$  in 010. Natural crystals of orthoclase (and sanidine) show a similar variation in the size of the optic angle.



FIGS. 195, 196. The optic orientation of adularia.

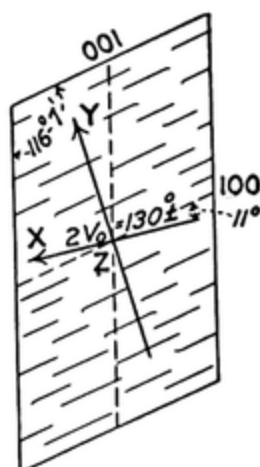


FIG. 197. The optic orientation of sodian adularia.

*Isorthoclase* is a rare kind of orthoclase which is optically positive. An example with  $(+ )2V = 86^\circ$ ,  $N_X = 1.523$ ,  $N_Z = 1.528$ ,  $N_Z - N_X = 0.005$  and  $X \wedge a = 0^\circ$  has been found in Virginia.<sup>86</sup>

*Hyalophane* or barian orthoclase contains 10–40%  $BaAl_2Si_2O_8$ . In it the optic plane is normal to 010, but the extinction angle in 010 ( $X \wedge a$ ) varies from about  $+2^\circ$  to about  $-25^\circ$ . See Fig. 198. This and other variations are shown in Fig. 188 and are tabulated as follows (data on  $Or_{90}Cn_{10}$  and  $Or_{70}Cn_{30}$  are from the graph):

	$Or_{90}Cn_{10}$	$Or_{87}Cn_{13}$	$Or_{70}Cn_{30}$
$(- )2V =$	$74^\circ$	$78^\circ$	$78^\circ$
$N_X =$	1.528	1.534	1.542
$N_Y =$	1.531	1.538	1.545
$N_Z =$	1.534	1.540	1.547
$N_Z - N_X =$	0.006	0.006	0.005
$X \wedge a =$	$+2^\circ$		$-25^\circ$
$G. =$	2.65	2.701	2.82

<sup>86</sup> T. F. W. Barth: *Am. Mineral.*, XVIII, 478 (1933). The optic angle varies from  $(- )2V = 10^\circ$  to  $(+ )2V = 86^\circ$ .



However, actual samples of hyalophane are likely to have properties not conforming exactly with this series because they contain appreciable amounts of  $NaAlSi_3O_8$ ,  $CaAl_2Si_2O_8$ , etc.

Orthoclase is colorless, white, pink, red, yellow, gray, or green in mass; the luster is vitreous. Colorless in thin section.

**INVER.** Orthoclase inverts to sanidine at about  $900^\circ$  to  $1150^\circ$ .

**ALTER.** Orthoclase alters rather easily to kaolinite or to sericite. The change occurs under both weathering and hydrothermal conditions. Quartz often forms at the same time. Much more rarely the alteration is to a zeolite, or chlorite, or, under exceptional conditions, to glauconite, alunite, or tourmaline.

**OCCUR.** Orthoclase is very abundant in acid plutonic rocks and common in plutonic rocks of intermediate acidity; it is also found in some volcanic rocks. It is common in contact zones and metamorphic rocks; it is not rare in clastic rocks. Orthoclase formed in veins is sometimes called *valencianite*. Regular intergrowths of orthoclase (or microcline) and albite, called *perthite*, are believed to be due to a secondary ("unmixing") process by which a homogeneous crystal separates (without fusion or solution) into unlike parts as a result of instability induced by cooling.

**DIAG.** Orthoclase, sanidine, and microcline have lower specific gravity and refringence than plagioclase. Being monoclinic, orthoclase and sanidine have a cleavage angle of exactly  $90^\circ$  and no multiple twinning, which is so common in plagioclase and microcline. Orthoclase in most samples has a smaller optic angle than found in plagioclase but a larger angle than in sanidine.

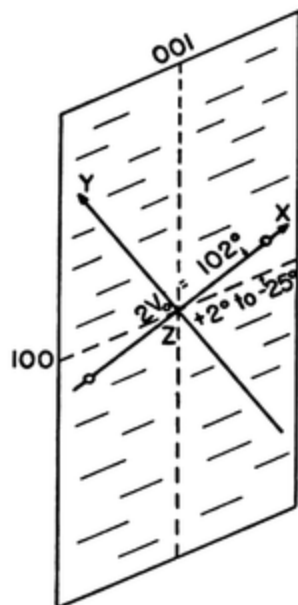
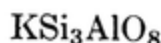


FIG. 198. The optic orientation of hyalophane.

## SANIDINE

### MONOCLINIC PRISMATIC



$$a:b:c = 0.652:1:0.551 \quad \beta = 115^\circ 35'$$

**COMP.** Sanidine varies in composition from the (nearly) pure compound to crystals with as much as 55%  $NaAlSi_3O_8$ , or up to at least 30%  $BaAl_2Si_2O_8$ , or small amounts of other molecules, such as  $CaAl_2Si_2O_8$ ,  $RbAlSi_3O_8$ ,  $KFeSi_3O_8$ , etc.

**STRUC.** Space group <sup>87</sup>  $C2/m$ ;  $a$  8.4,  $b$  12.9,  $c$  7.1 Å. U.C. 4.

**PHYS. CHAR.** Crystals often tabular parallel to  $\{010\}$  or elongated

<sup>87</sup> W. H. Taylor: *Zeit. Krist.*, LXXXV, 425 (1933).

along  $a$  with {001} and {010}. Carlsbad twinning common; Baveno and Manebach twinning uncommon. Perfect 001 and distinct 010 cleavages.  $H. = 6$ .  $G. = 2.57$ . Insoluble in acid.

**OPT. PROP.** In some crystals of sanidine the optic plane and  $Z$  are normal to 010; in others the optic plane is parallel with 010; the optic angle is always small, and may vary through  $0^\circ$ , this variation being accompanied by a change in the position of the optic plane. The optic plane may be normal to 010 in red light and parallel thereto in blue light. If the optic plane is parallel with 010 (as in Fig. 199) the dispersion is inclined (weak) with  $r > v$ ; if it is normal to 010 the dispersion is horizontal (weak) with  $r < v$ . The acute bisectrix,  $X$ , makes an angle of about  $5^\circ$  (to  $8^\circ$ ) with  $a$  (the trace of the basal cleavage) in 010.

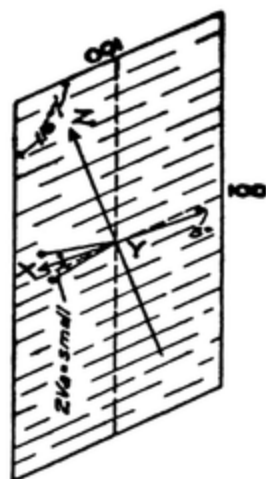


FIG. 199. The optic orientation of sanidine.

$(- )2V = \text{small}$ ,  $N_X = 1.520\text{--}1.523$ ,  $N_Y \approx N_Z$ ,  $N_Z = 1.525\text{--}1.53$ ,  $N_Z - N_X = 0.005\text{--}0.006$ .

The refringence, birefringence, extinction angle, and specific gravity increase with increase of sodium—see Fig. 191, but apparently not as fast as in orthoclase.

**ISOSANIDINE**, characterized by being optically positive (with small optic angle and  $Z$  normal to 010) has been reported,<sup>88</sup> but is very rare.

Barian sanidine may contain about 10 to 40%  $\text{BaAl}_2\text{Si}_2\text{O}_8$ . A sample<sup>89</sup> with about 10%  $\text{BaAl}_2\text{Si}_2\text{O}_8$  has the optic plane and  $Z$  normal to 010;  $X \wedge a = 25^\circ$ ,  $N_X = 1.536$ ,  $N_Y = 1.542$ ,  $N_Z = 1.546$ ,  $N_Z - N_X = 0.010$ .

Sanidine is colorless, white, or tinted in mass; luster vitreous. Colorless in thin section.

**INVER.** See orthoclase.

**ALTER.** Sanidine alters easily to kaolinite or sericite, often with simultaneous formation of quartz. Other alteration products are possible.

**OCCUR.** Sanidine is abundant in some acid volcanic rocks and common in some volcanic rocks of intermediate acidity.

**DIAG.** Sanidine has the smallest optic angle known in feldspar.<sup>90</sup> In some samples the optic angle may be about as large as found in anorthoclase. Sanidine has no multiple twinning. Sanidine, orthoclase, and

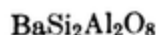
<sup>88</sup> L. Duparc: *Comp. Rend. Acad. Sci. Paris*, CXXXVIII, 714 (1904).

<sup>89</sup> E. S. Larsen et al.: *Bull. Geol. Soc. Am.*, LII, 1841 (1941).

<sup>90</sup> G. A. Macdonald described a plagioclase with  $2V$  about  $50^\circ$  or less, but it is optically positive. See *Am. Mineral.*, XXVII, 793 (1942).

microcline have the lowest refringence and lowest specific gravity found in feldspars.

**Barbierite**<sup>79</sup> ( $NaSi_3AlO_8$ ) is monoclinic<sup>91</sup> with  $a:b:c = 0.615:1:0.552$ ,  $\beta = 116^\circ$ .  $a$  7.94,  $b$  12.90,  $c$  7.12 Å. Found by Ito in moonstone. Studied only by X-ray methods. See Fig. 190.

**CELSIAN****MONOCLINIC PRISMATIC**

$$a:b:c = 0.658:1:0.549 \quad \beta = 115^\circ 9'$$

**STRUC.** Space group<sup>92,93</sup>  $C2/m$ ;  $a$  8.63,  $b$  13.10,  $c$  7.29 Å. U.C. 4.

**PHYS. CHAR.** Crystals short prismatic with prominent prism faces as in adularia. Perfect 001, distinct 010, and poor 110 cleavages. Carlsbad, Baveno, and Manebach twinning.  $H. = 6$ .  $G. = 3.2-3.45$ .  $F. = 7$ . Soluble in HCl.

**OPT. PROP.** The optic plane<sup>93</sup> is 010;  $Z \wedge a$  (the 001 cleavage)  $= +28^\circ$ ;  $X \wedge c = +3^\circ$ . See Fig. 200.  $N_X = 1.580$ ,  $N_Y = ?$ ,  $N_Z = 1.590$ . Also:<sup>94</sup>  $Z \wedge a = 30^\circ$ ,  $(+)2V = \text{near } 90^\circ$ ,  $N_X = 1.584$ ,  $N_Y = 1.589$ ,  $N_Z = 1.596$ .  $N_Z - N_X = 0.012$ . Artificial  $BaAl_2Si_2O_8$  has<sup>95</sup>  $N_X = 1.587$ ,  $N_Y = 1.593$ ,  $N_Z = 1.600$ ,  $N_Z - N_X = 0.013$ . Celsian<sup>96</sup> with 94 per cent Cn has  $N_X = 1.5835$ ,  $N_Y = 1.5886$ ,  $N_Z = 1.594$ ,  $N_Z - N_X = 0.0106$ , and  $(+)2V = 86^\circ 22'$ . Relations with adularia are shown in Fig. 188.

Colorless or yellow. Luster vitreous. Colorless in section.

**INVER.** Ginsberg<sup>97</sup> reported that  $BaAl_2Si_2O_8$  crystallizes at low temperature in hexagonal plates; it is uniaxial<sup>98</sup> negative with  $N_O = 1.5712$ . However, Spencer<sup>93</sup> found an apparently orthorhombic phase of  $BaAl_2Si_2O_8$  in Wales which he called *paracelsian*; its crystals are large, well-formed, resembling topaz, and have  $a:b:c = 0.947:1:0.896$ . They have poor 110 cleavage and complex multiple twinning.  $G. = 3.31-3.32$ . Optically monoclinic with  $Y \wedge c = 4.5^\circ$ ;  $Z = b$ .  $(-)2V = 50^\circ$ ,  $r < v$ ,  $N_X = 1.5702$ ,  $N_Y = 1.5824$ ,  $N_Z = 1.5869$ ,  $N_Z - N_X = 0.0167$ . Colorless.

Found in a band in shale and sandstone. A variety of celsian<sup>99</sup> containing about 4% CaO has:  $Y = b$ ,  $Z \wedge a = 29^\circ$ ,  $(-)2V = 76^\circ$ ,  $N_Z = 1.572$ ,  $N_Y = 1.5795$  (calc.),  $N_Z = 1.584$ ,  $N_Z - N_X = 0.012$ .

**OCCUR.** Celsian is found in contact zones as at Jakobsberg, Sweden; near Incline, California; and in Japan and Wales.

<sup>91</sup> T. Ito: *Zeit. Krist., C*, 297 (1938).

<sup>92</sup> E. Schiebold: *Zeit. Krist.*, LXVI, 488 (1928).

<sup>93</sup> L. J. Spencer: *Mineral. Mag.*, XXVI, 231 (1942).

<sup>94</sup> W. T. Schaller: *Am. Mineral.*, XIV, 319 (1929).

<sup>95</sup> P. Eskola: *Am. Jour. Sci.*, CCIV, 331 (1922).

<sup>96</sup> J. E. Strandmark: *Geol. För. Förh.*, XXV, 289 (1903); XXVI, 97 (1904); *Zeit. Krist.*, XLIII, 89 (1906).

<sup>97</sup> A. S. Ginsberg: *Min. Abst.*, II, 153 (1923).

<sup>98</sup> E. Dittler and H. Lasch: *Min. Abst.*, V, 102 (1933).

<sup>99</sup> E. R. Segnit: *Mineral. Mag.*, XXVII, 166 (1946).

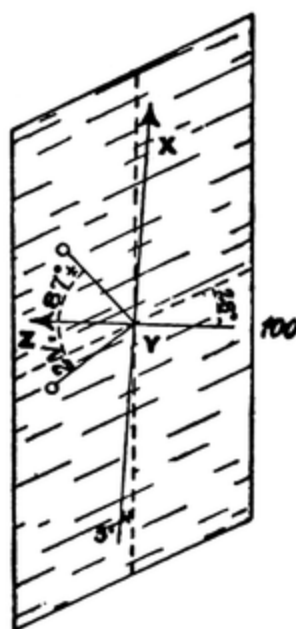


FIG. 200. The optic orientation of celsian.

**DIAG.** Celsian differs from orthoclase and hyalophane in optic sign, large extinction angle in sections or cleavage fragments parallel to 010, higher specific gravity, and ready solubility. It also has moderate relief and birefringence.

**Kasoite** is a barium feldspar<sup>74</sup> near  $\text{Ca}_{50}(\text{Or}, \text{Ab})_{50}$  (but with deficiency in  $\text{SiO}_2$ ) which has  $G. = 3.0$ ,  $(-2V) = 80^\circ$ ,  $N_X = 1.564$ ,  $N_Y = 1.568$ ,  $N_Z = 1.572$ ,  $N_Z - N_X = 0.008$ ; the optic plane is parallel with 010 (or nearly so),  $X \wedge c = 2^\circ - 3^\circ$  in acute angle  $\beta$ ,  $Z \wedge a$  on 011 =  $28^\circ - 29^\circ$  in obtuse angle  $\beta$ ; the extinction angle on 001 is  $10^\circ - 13^\circ$  (therefore triclinic). Found at the Kaso mine in Japan.

## MICROCLINE



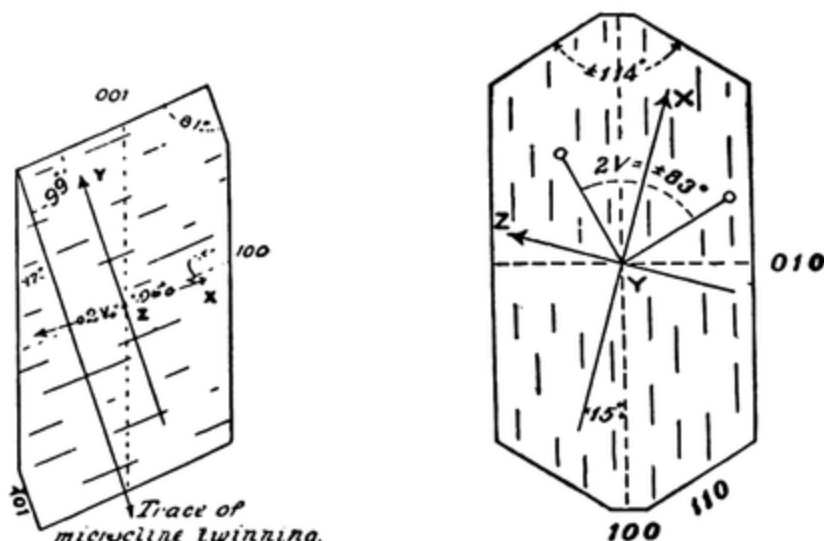
### TRICLINIC PINACOIDAL (PSEUDOMONOCLINIC)

$$a:b:c = 0.649:1:0.554 \quad \alpha = 90^\circ 7' \quad \beta = 115^\circ 50' \quad \gamma = 89^\circ 55'$$

**COMP.** Natural microcline is practically never composed solely of  $\text{KAlSi}_3\text{O}_8$ , but usually contains about 20 per cent of  $\text{NaAlSi}_3\text{O}_8$ , besides very small amounts of other molecules, such as  $\text{CaAl}_2\text{Si}_2\text{O}_8$ , etc.

**STRUC.** Space group<sup>92</sup>  $P\bar{1}$ ;  $a$  8.44,  $b$  13.00,  $c$  7.21 Å. U.C. 4.

**PHYS. CHAR.** Crystals of microcline are very similar to those of orthoclase. They show simple twinning of the Carlsbad, Baveno, and



FIGS. 201, 202. The approximate optic orientation of microcline.

Manebach types, and fine microscopic lamellar twinning of the albite and pericline types. The composition face of the pericline twinning makes an angle of  $+99^\circ$  with 001 in 010. Microcline has perfect 001 and distinct 010 cleavages.  $H. = 6$ .  $G. = 2.55$ . Fusion of pure  $\text{KAlSi}_3\text{O}_8$  begins at  $1170^\circ$  with formation of leucite;<sup>100</sup> fusion is complete at  $1530^\circ$  (pure) and about  $1450^\circ$  (natural). Insoluble in acid.

<sup>100</sup> G. W. Morey and N. L. Bowen: *Am. Jour. Sci.*, CCIV, 1 (1922).

OPT. PROP. The optic plane and Z are nearly normal to 010; the negative acute bisectrix X makes an angle of about  $+5^\circ$  in 010 with 001 (cleavage). The extinction angle in 001 is about  $+15^\circ$  from the 010 cleavage. The extinction angle referred to the trace of the optic plane

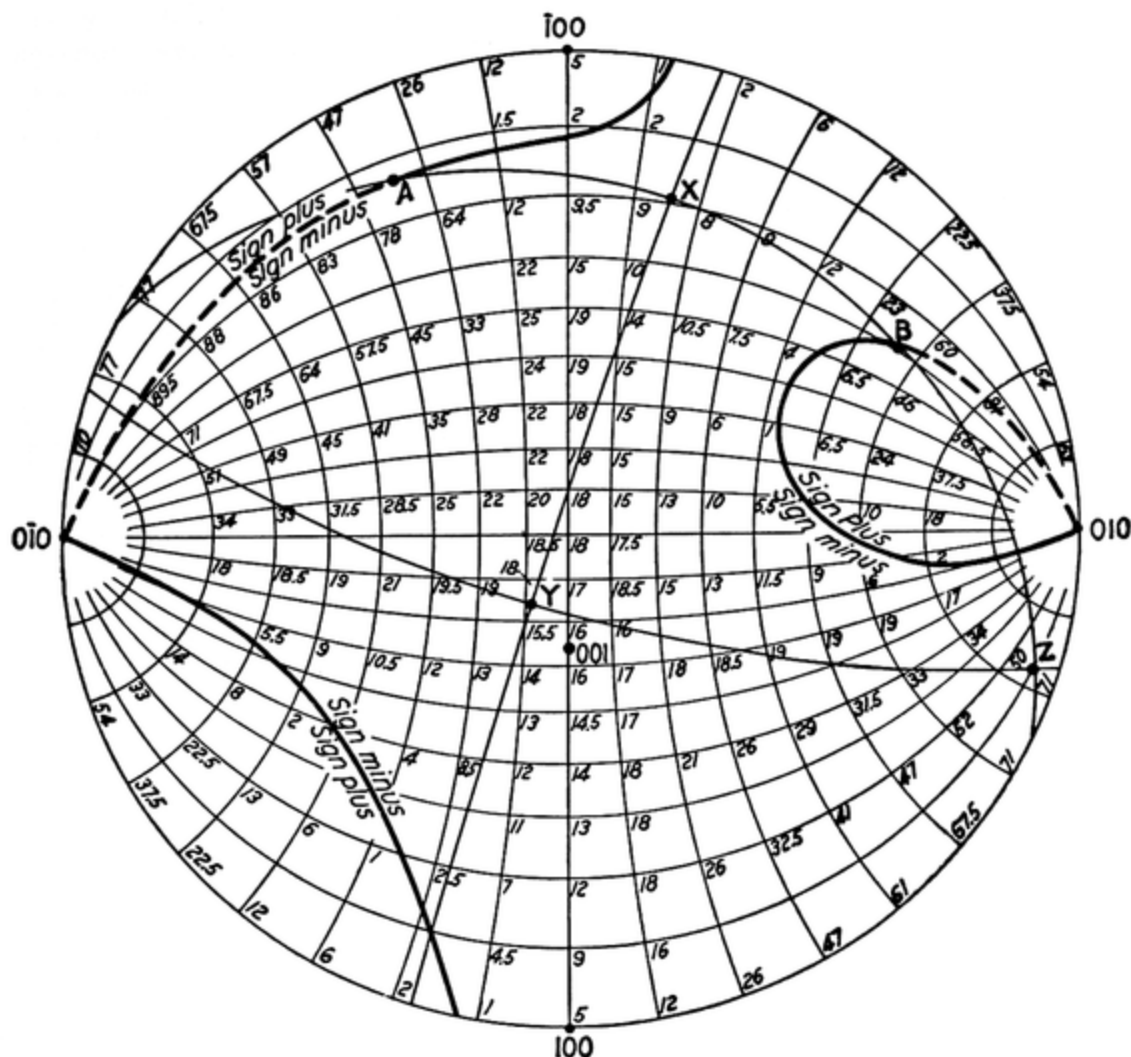


FIG. 203. Stereographic projection showing extinction angles ( $X' \cap 010$ ) of microcline. [Modified from Rosenbusch-Wülfing: *Mikro. Phys.*, I, 2 (1905).] (Correction: interchange "Sign plus" and "Sign minus").

in a section normal to X is  $88^\circ$  and in a section normal to Z is  $+10^\circ$ . The optic angle is large with notable horizontal dispersion and  $r > v$ . See Figs. 192, 201–203.  $(- )2V = 83^\circ \pm$ ,  $N_X = 1.518$ ,  $N_Y = 1.522$ ,  $N_Z = 1.525$ ,  $N_Z - N_X = 0.007$ .

*Isomicrocline*<sup>101</sup> is the name given to a very rare variety which is optically positive, though otherwise like normal microcline.

INVER. Microcline is stable to its melting point, according to

<sup>101</sup> W. Luczizky: *Tsch. Min. Pet. Mit.*, XXIV, 347 (1905).

Merwin,<sup>76</sup> but inverts to orthoclase at  $1000^{\circ}+$  after 500–700 hours according to Dittler and Köhler.<sup>102</sup>

**ALTER.** The alteration of microcline to sericite, albite, and quartz is rather common; microcline alters as easily and in the same way as orthoclase.

**OCCUR.** Microcline is formed under the same general conditions as orthoclase (except that it is favored by shearing?); it is especially common in pegmatite, and in shear zones, according to Alling.<sup>77</sup> See



FIG. 204. Photomicrograph of microcline in thin section, with some plagioclase.  $\times 50$ .

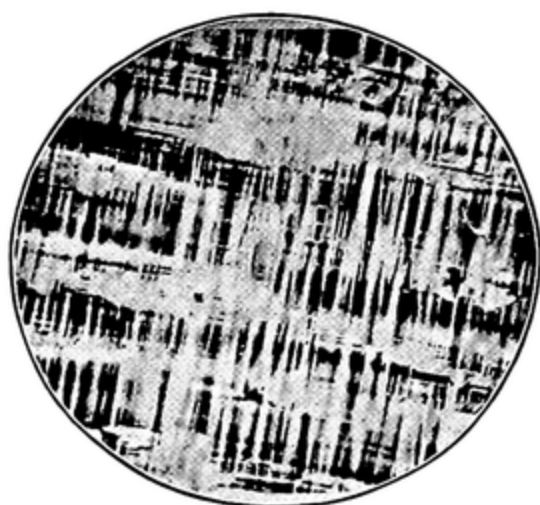


FIG. 205. Photomicrograph of microcline-perthite in thin section. Taken by H. L. Alling; see *Jour. Geol.*, XXIX, 193 (1921).

Figs. 204 and 205. Regular intergrowths with albite (called *microcline-perthite*) are similar in type and origin to those of orthoclase.

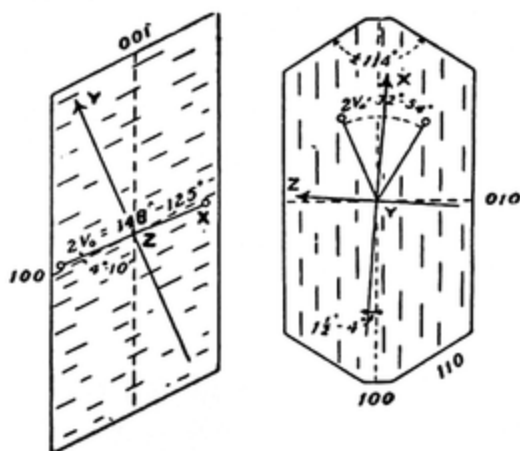
**DIAG.** Microcline is characterized by the quadrille structure due to two sets of microscopic lamellar twinning, which are nearly at right angles. Lamellar twinning is not found in monoclinic feldspars. One set of such twinning is extremely common and two sets are not rare in plagioclase feldspar, but, in the latter, one set (pericline) makes a small angle with 001 and is therefore invisible in sections or cleavage pieces parallel with 001 whereas in microcline the corresponding twinning is nearly normal to 001 and therefore distinct in sections or cleavage plates parallel with the basal cleavage. Furthermore, the twinning of microcline wedges out in both directions while that of plagioclase is more continuous and tends to end abruptly against another twinning band. Microcline devoid of multiple twinning is quite rare, but not unknown.

<sup>102</sup> E. Dittler and A. Köhler: *Tsch. Min. Pet. Mit.*, XXXVIII, 229 (1925).



**ANORTHOCLASE** TRICLINIC PINACOIDAL (PSEUDOMONOCLINIC)  $(Na,K)Si_3AlO_8$   
 $a:b:c$  <sup>103</sup> = 0.645:1:0.557     $\alpha = 91^\circ 19'$      $\beta = 116^\circ 57'$      $\gamma = 90^\circ 0'$

**COMP.** Anorthoclase is chemically much nearer to albite than to orthoclase; the name is due to the fact that it is microscopically much like, but distinguishable from, orthoclase. If it contains less than 10%  $KAlSi_3O_8$  the name *analbite* has been suggested.<sup>80</sup> When the twinning is well developed anorthoclase closely resembles microcline in thin section. Small amounts of other molecules, especially  $CaAl_2Si_2O_8$ , are common.



FIGS. 206, 207. The optic orientation of anorthoclase.

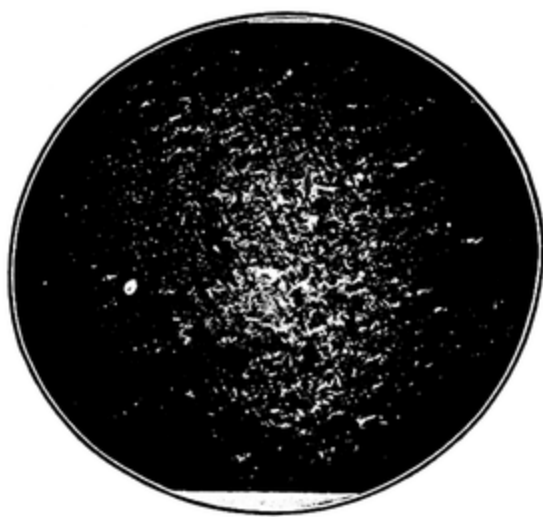


FIG. 208. Photomicrograph of anorthoclase in thin section.  $\times 25$ . Taken by H. L. Alling; see *Jour. Geol.*, XXIX, 193 (1921).  $\times 25$ .

**PHYS. CHAR.** Crystals of anorthoclase are similar to those of orthoclase. In some rocks ("rhomb porphyries") crystals have only the faces  $\{110\}$ ,  $\{1\bar{1}0\}$ , and  $\{201\}$ . Twinning is on the Carlsbad, Baveno, and Manebach laws; Carlsbad twins of the rhomb porphyries have 100 as the composition face. The characteristic twinning of anorthoclase is the combination of the albite and pericline lamellar types, differing from microcline only in the extreme narrowness of the albite bands. The composition face of the pericline twinning in anorthoclase makes an angle of  $-75^\circ$  to  $-78^\circ$  with 001 in 010. Twinning on an axis normal to  $\bar{2}01$  is often also present. Anorthoclase free of multiple twinning is rare and difficult to recognize. Anorthoclase has perfect 001 and distinct 010 cleavages.  $H. = 6$ .  $G. = 2.56-2.6$ .  $F. = 5$ . Insoluble in acid.

**OPT. PROP.** The optic plane is nearly normal to 010, and the negative acute bisectrix X makes an angle of  $+6^\circ$  to  $+12^\circ$  with  $a (= 001 \text{ cleavage})$  in 010. The extinction angle in 001 is  $+1^\circ$  to  $+6^\circ$ , usually  $1^\circ-3^\circ$ , whereas the extinction angle referred to the optic plane in sections normal to X is  $80^\circ$  to  $89^\circ$ , and in sections normal to Z is about  $9^\circ$ . See Figs. 206 and 207. Distinct horizontal dispersion.  $(-)2V = 42^\circ$  to  $54^\circ$ ,  $r > v$ ,  $N_X = 1.523$ ,  $N_Y = 1.528$ ,  $N_Z = 1.529$ ,  $N_Z - N_X = 0.006$ . Again <sup>104</sup>  $(-)2V = 60^\circ$ ,  $N_X = 1.5198$ ,  $N_Y = 1.5242$ ,  $N_Z = 1.5276$ ,  $N_Z - N_X = 0.0078$ .

<sup>103</sup> M. Montalto: *Min. Abst.*, VII, 294 (1939).

<sup>104</sup> T. L. Ho: *Min. Abst.*, V, 439 (1934).

Colorless or tinted; Colorless in section. Internal reflections ("moonstone") are rare.

**INVER.** Anorthoclase is stable to its melting point.<sup>76</sup>

**ALTER.** The methods and products of alteration are similar to those of albite.

**OCCUR.** Anorthoclase is found only in volcanic rocks rich in soda; it is often intergrown with sanidine.

**DIAG.** The quadrille structure due to two sets of lamellar twinning is nearly always present, and is composed of bands which are extremely narrow even as seen microscopically. See Fig. 208. The extinction angle in 001 (about 2°) is much smaller than in microcline (15°), the maximum equal extinction angle in the zone normal to 010 is 1° to 2°, and the optic angle is the smallest found in the feldspar group except for sanidine (and K<sub>2</sub>O-rich plagioclase<sup>105</sup>).

### PLAGIOCLASE TRICLINIC PINACOIDAL<sup>105a</sup> NaSi<sub>3</sub>AlO<sub>8</sub> to CaSi<sub>2</sub>Al<sub>2</sub>O<sub>8</sub>

<b>Albite</b>	Ab <sub>100</sub> An <sub>0</sub> to Ab <sub>90</sub> An <sub>10</sub>
<b>Oligoclase</b>	Ab <sub>90</sub> An <sub>10</sub> to Ab <sub>70</sub> An <sub>30</sub>
<b>Andesine</b>	Ab <sub>70</sub> An <sub>30</sub> to Ab <sub>50</sub> An <sub>50</sub>
<b>Labradorite</b>	Ab <sub>50</sub> An <sub>50</sub> to Ab <sub>30</sub> An <sub>70</sub>
<b>Bytownite</b>	Ab <sub>30</sub> An <sub>70</sub> to Ab <sub>10</sub> An <sub>90</sub>
<b>Anorthite</b>	Ab <sub>10</sub> An <sub>90</sub> to Ab <sub>0</sub> An <sub>100</sub>

**COMP.** A continuous series<sup>81</sup> is known, both in nature and in artificial crystals, from pure albite (NaAlSi<sub>3</sub>O<sub>8</sub> = Ab) to pure anorthite (CaAl<sub>2</sub>Si<sub>2</sub>O<sub>8</sub> = An); natural crystals usually contain also a small tenor of potassium as KAlSi<sub>3</sub>O<sub>8</sub> (= Or) as well as very small amounts of other elements, such as Rb (in RbAlSi<sub>3</sub>O<sub>8</sub>). See Fig. 149 on page 264.

**STRUC.** Space group<sup>106</sup>  $P\bar{1}$ , U.C. 8.

	<i>a</i>	<i>b</i>	<i>c</i>	$\alpha$	$\beta$	$\gamma$
Albite	8.23	13.00	7.25	94° 3'	116° 29'	88° 9'
Oligoclase	8.16	12.90	7.13	93° 4'	116° 22'	90° 4'
Andesine	8.14	12.86	7.17	93° 23'	116° 28'	89° 59'
Labradorite	8.21	12.95	14.16	93° 31'	116° 3'	89° 55'
Anorthite	8.21	12.95	14.16	93° 13'	115° 56'	91° 12'

**PHYS. CHAR.** Crystals of plagioclase are commonly tabular parallel to 010, and sometimes elongated parallel to *a*; in "rhomb porphyries" and rarely in other rocks the elongation is parallel to *c* and the crystals are prismatic, the only faces being {110}, {1 $\bar{1}$ 0}, {201}, and perhaps small {001}. Perfect 001 and distinct 010 cleavages. The albite twinning is especially characteristic, but may be absent; other types of twinning which are not uncommon include pericline, Carlsbad, Baveno, and Manebach. *H.* = 6–6.5. *G.* = 2.61–2.76. *F.* = 1100° (albite) to 1550° (anorthite). Albite, oligoclase, and andesine are insoluble in

<sup>105</sup> G. A. Macdonald: *Am. Mineral.*, XXVII, 793 (1942).

<sup>105a</sup> Axial ratios are given on page 265.

<sup>106</sup> W. H. Taylor *et al.*: *Zeit. Krist.*, LXXXV, 425 (1933), LXXXVII, 464 (1934), and *Proc. Roy. Soc. London, A*, CLXXVI, 76 (1940).

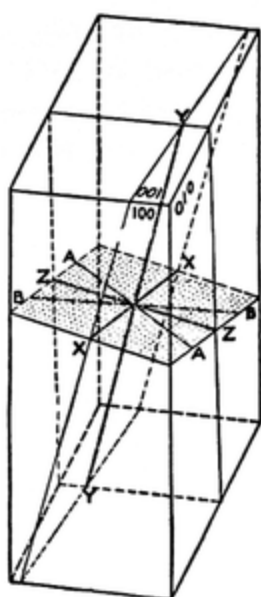


FIG. 209. The optic orientation of albite.

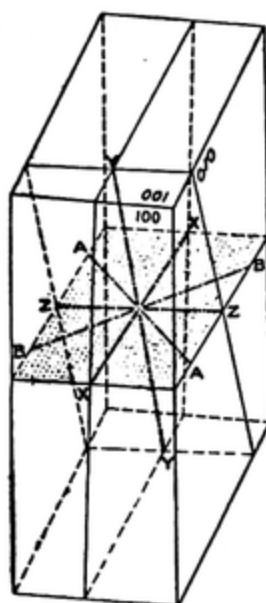


FIG. 210. The optic orientation of oligoclase.

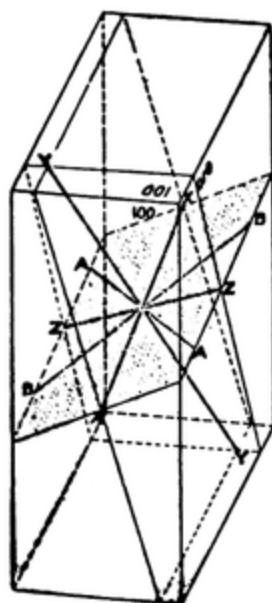


FIG. 211. The optic orientation of andesine.

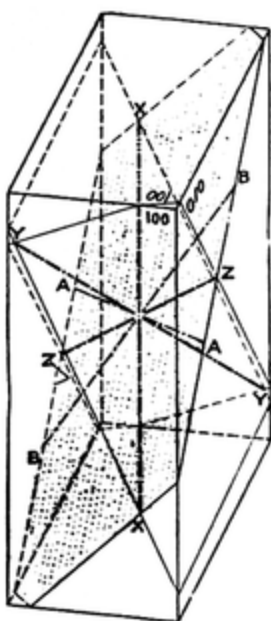


FIG. 212. The optic orientation of labradorite.

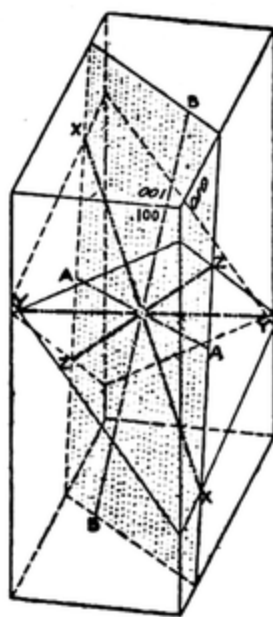


FIG. 213. The optic orientation of bytownite.

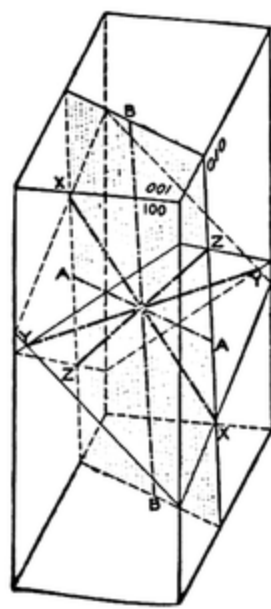


FIG. 214. The optic orientation of anorthite.

acids (except HF); labradorite is very slowly attacked; bytownite is attacked gradually; anorthite is easily decomposed with separation of gelatinous silica.

OPT. PROP. The optic orientation varies considerably from albite to anorthite, but in the whole series the axis Z is nearer to a normal to 010 than is X or Y and the bisectrix (Z) interference figure is visible



from labradorite to anorthite; the dispersion of the bisectrices varies in different types, but is never great, though showing two kinds, and therefore no symmetry, in accordance with the triclinic character of plagioclase.

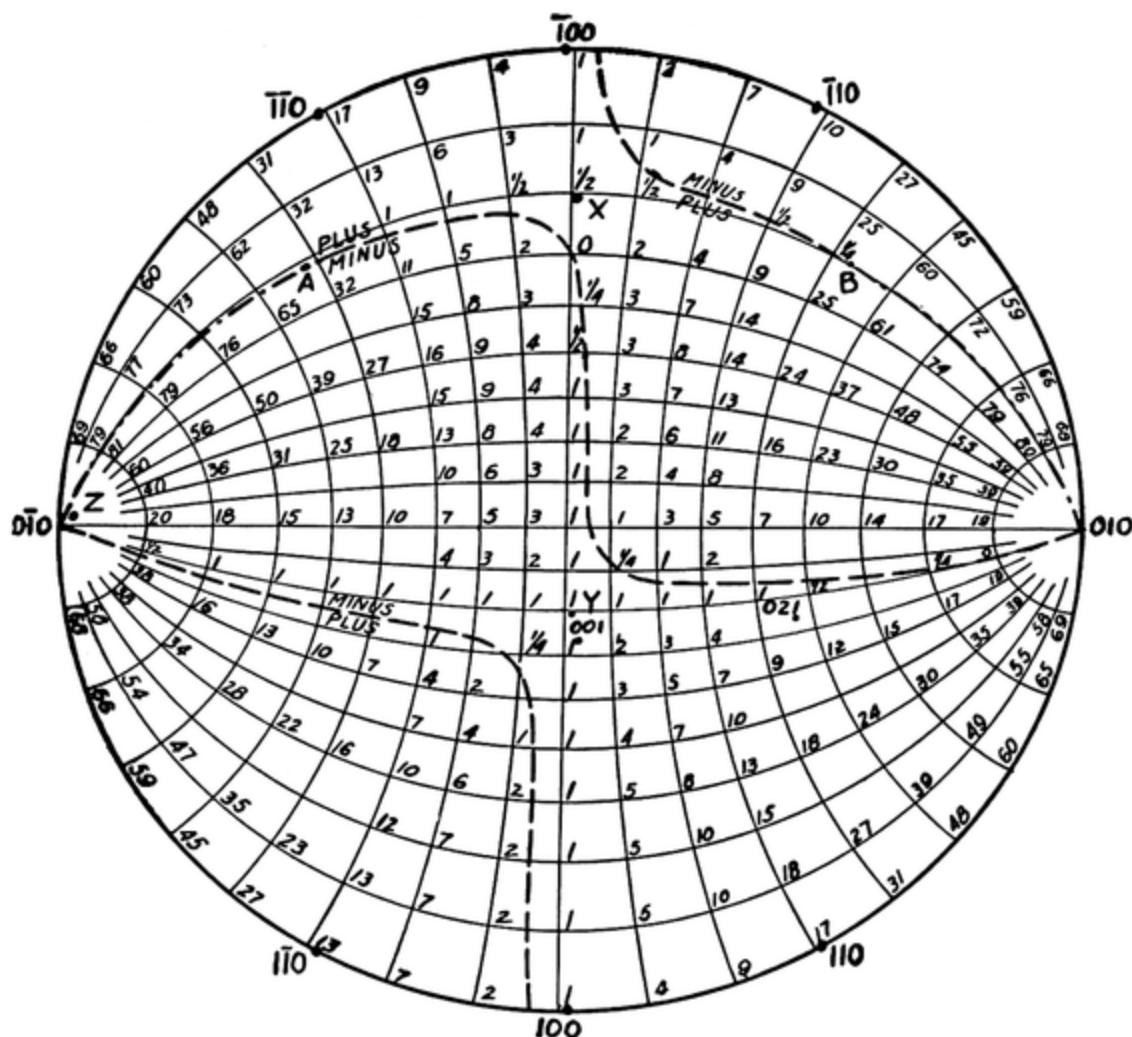


FIG. 215a. Stereographic projection showing extinction angles ( $X' \cap 010$ ) of oligoclase ( $Ab_{80}An_{20}$ ). (After Duparc and Reinhard.) (Correction: interchange "Plus" and "Minus.")

The indices of refraction increase with increasing tenor of anorthite, as shown in Fig. 148 and in the table on page 276, as well as in the table which follows. The birefringence decreases from 0.011 in albite to 0.007 in andesine and then increases to 0.013 in anorthite, as shown on page 276 and in the following table. Important extinction angles are shown on page 316.

Plagioclase with a small optic angle (from  $60^\circ$  down to about  $10^\circ$ ) is found in some volcanic rocks; it is otherwise like oligoclase or andesine; the small optic angle is probably due <sup>105</sup> to  $KAlSi_3O_8$  in crystal solution

## SOME OPTICAL PROPERTIES OF PLAGIOCLASE

	Albite	Albite	Oligoclase	Andeclase	Andesine	Labradorite	Labradorite	Bytownite	Bytown-orthite	Anorthite
	Ab <sub>95</sub> An <sub>5</sub>	Ab <sub>85</sub> An <sub>15</sub>	Ab <sub>75</sub> An <sub>25</sub>	Ab <sub>65</sub> An <sub>35</sub>	Ab <sub>55</sub> An <sub>45</sub>	Ab <sub>45</sub> An <sub>55</sub>	Ab <sub>35</sub> An <sub>65</sub>	Ab <sub>25</sub> An <sub>75</sub>	Ab <sub>15</sub> An <sub>85</sub>	Ab <sub>5</sub> An <sub>95</sub>
2V =	(+)76°	(+)87°	(-)82°	(-)85°	(+)88°	(+)75°	(+)86°	(-)86°	(-)79°	(-)77°
N <sub>x</sub> =	1.529	1.536	1.542	1.547	1.553	1.557	1.561	1.565	1.568	1.573
N <sub>y</sub> =	1.532	1.540	1.546	1.551	1.556	1.560	1.565	1.570	1.574	1.580
N <sub>z</sub> =	1.539	1.544	1.549	1.554	1.560	1.565	1.570	1.574	1.578	1.585
N <sub>z</sub> - N <sub>x</sub> =	0.010	0.008	0.007	0.007	0.007	0.008	0.009	0.009	0.010	0.012

## Extinction Angles

	Albite	Albite	Oligoclase	Andeclase	Andesine	Labradorite	Labradorite	Bytownite	Bytown-orthite	Anorthite
	Ab <sub>95</sub> An <sub>5</sub>	Ab <sub>85</sub> An <sub>15</sub>	Ab <sub>75</sub> An <sub>25</sub>	Ab <sub>65</sub> An <sub>35</sub>	Ab <sub>55</sub> An <sub>45</sub>	Ab <sub>45</sub> An <sub>55</sub>	Ab <sub>35</sub> An <sub>65</sub>	Ab <sub>25</sub> An <sub>75</sub>	Ab <sub>15</sub> An <sub>85</sub>	Ab <sub>5</sub> An <sub>95</sub>
⊥ X	+75°	+84°	-86°	-73°	-67°	-63°	-60°	-58°	-57°	-58°
⊥ Y (X ∧ 010)	0°	+1°	+1°	-1°	-7°	-18°	-22°	-29°	-35°	-40°
⊥ Z	+21°	+12°	+3°	-7°	-19°	-30°	-40°	-49°	-57°	-62°
∥ 001	+2°	+2°	0°	-2°	-4°	-8°	-12°	-18°	-27°	-35°
∥ 010	+18°	+12°	+3°	-4°	-12°	-18°	-25°	-31°	-35°	-37°
Max. ⊥ 010	-15°	-8°	+7°	+17°	+25°	+31°	+37°	+42°	+48°	+56°





Recognizing the possibility of measuring in thin sections not only the two extinction angles in a twin but also the ratio of birefringences of the two individuals, Nieuwenkamp rearranged the data of Nikitin<sup>108</sup> in a series of ten charts on the cylindrical equidistant projection of the hemisphere, showing, with two sets of contour lines, the extinction angles  $X' \wedge 010$ , and the logarithms of birefringences,

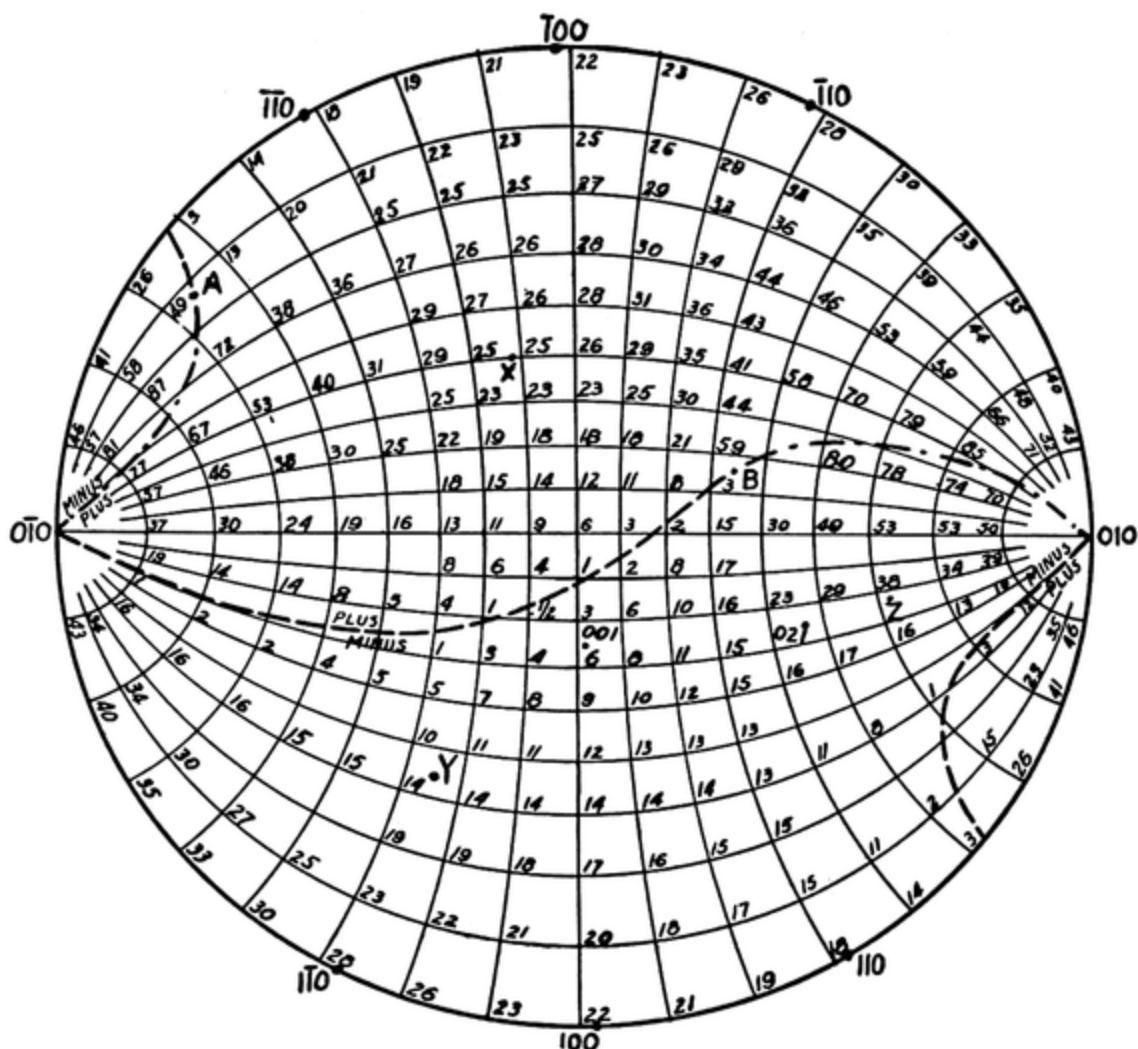


FIG. 215c. Stereographic projection showing extinction angles ( $X' \wedge 010$ ) of labradorite ( $Ab_{48}An_{52}$ ). (After Duparc and Reinhard.)

for all orientations. The equator or lower base line of each projection represents the trace of 010 on the surface of a sphere; the entire upper edge represents the pole or normal to 010. Angular coordinates shown along the bottom and left sides of the charts give the orientation of the normal to the thin section and therefore of the wave-normal for rays of light passing through it along the axis of the microscope. Nieuwenkamp's ten principal charts show the properties of the members of the plagioclase series that have compositions of 0, 10, 20, ..., 80, and 95% anorthite. They are reproduced<sup>107</sup> here on a small scale, omitting much detail, in Figs. 218a to 222b. Extinction angles are indicated by solid contours; logarithms

<sup>108</sup> W. W. Nikitin: *Federow Methode*, Berlin, 1936.



therefore (from the chart) the optical properties, of the two individuals of an albite twin for any orientation of the section. In practice successive charts are tried, until the extinction angles observed in the two parts of the thin section of an albite twin of unknown composition agree or coincide with those shown at the two ends of the pointer. Such coincidences usually occur at more than one position of the pointer,

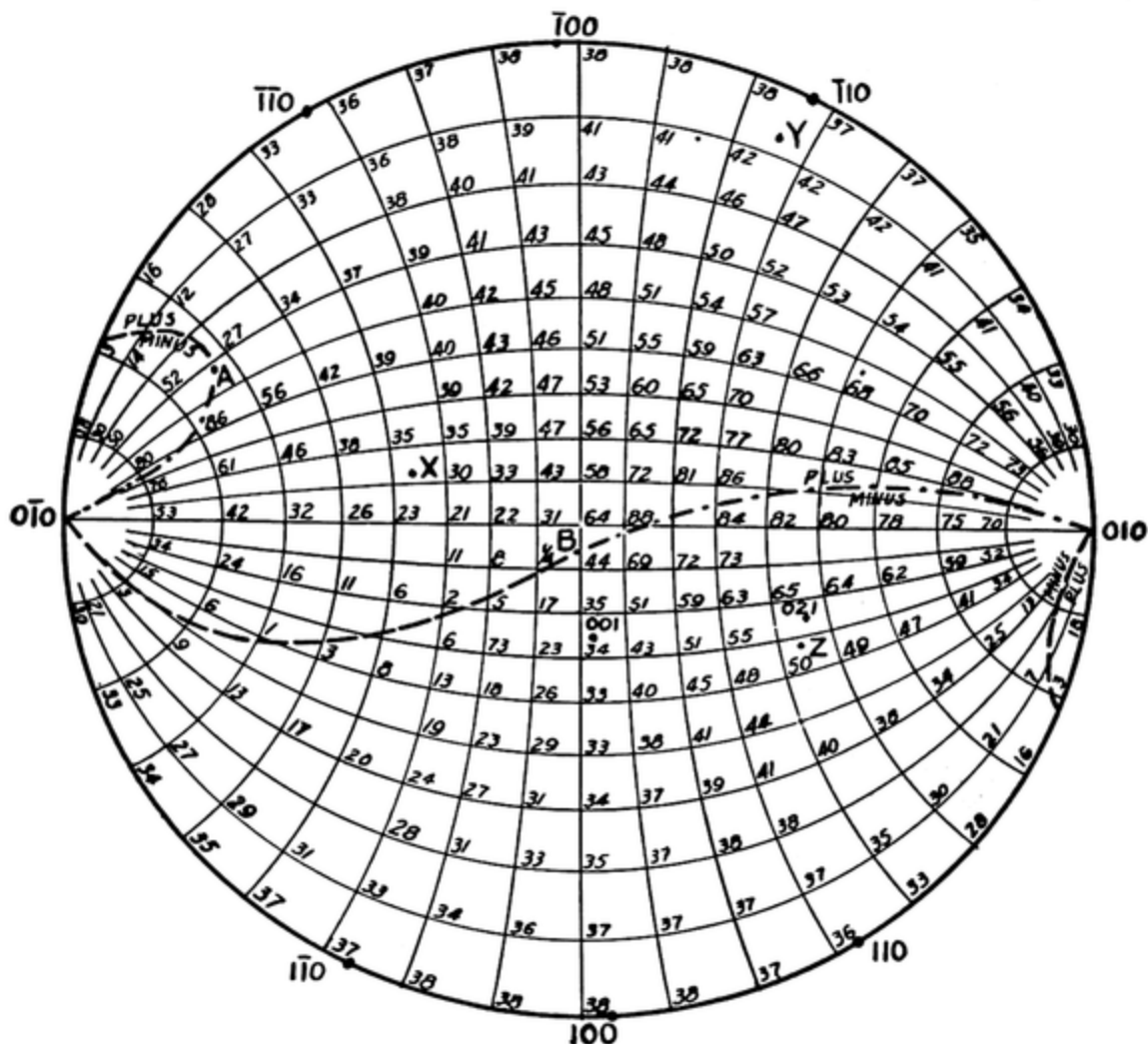


FIG. 215e. Stereographic projection showing extinction angles ( $X' \wedge 010$ ) of anorthite ( $Ab_3An_{97}$ ). (After Duparc and Reinhard.)

or on more than one chart, or both. Some are immediately eliminated by consideration of the likeness or difference of signs of the two extinction angles, for, even though the sign of one extinction angle may be in doubt, it can be compared with that of the other without the correct sign of either one being known. Other coincidences can be eliminated by noting whether the composition plane of the twin appears clear, narrow, and sharp, showing it to be nearly vertical, or otherwise. For every remaining coincidence the difference between the logarithms of birefringence, read at the ends of the pointer, is compared with the logarithm of the ratio of birefringences observed in the section, either eliminating all but one chart which gives the composition directly, or eliminating all but two adjacent charts for which the chart values of the log-birefringence-ratio are near, but on opposite sides of, the observed

value. Interpolation between compositions shown on these two charts then gives the composition of the unknown plagioclase.

The ratio of birefringences  $(B_2/B_1)^{108a}$  of the two twin-individuals can be determined without knowing the actual birefringences  $B_1$  and  $B_2$ . Measurement of the latter would depend upon a knowledge of the thickness,  $t$ , of the section. But  $t$  is canceled out in forming the ratio  $B_2/B_1 = (\Delta_2/t) \div (\Delta_1/t)$ , where  $\Delta_2$  and  $\Delta_1$  are the retardations produced in the two twin-individuals. The retardations  $\Delta_2$  and  $\Delta_1$  may be measured by means of a Berek compensator or a graduated quartz wedge, or their ratio can sometimes be determined from a measurement of the position at which the two twin-individuals show equal illumination between crossed nicols.



FIG. 216. Photomicrograph of labradorite in thin section. Taken by H. L. Alling; see *Jour. Geol.*, XXIX, 193 (1921).



FIG. 217. Photomicrograph of zonal andesine in thin section.  $\times 50$ .

The *logarithm* of the ratio of birefringences of the two twin individuals is more convenient than the ratio itself because the difference of two values read from the charts is easier to obtain than the quotient. Only the first two decimal places of the mantissa need be considered. From the thin section, this logarithmic ratio is obtainable most easily and accurately from the readings of a Berek compensator by the use of the logarithmic table supplied by the makers of the compensator. It also may always be obtained from readings by means of a graduated quartz wedge. If the highest interference color in the twinned crystal is not too high, and especially if the ratio is comparatively large, then the measurement can also be obtained from the angles  $x_1$  and  $x_2$  between the position of equal illumination and the extinction positions of individuals 1 and 2 having apparent birefringences  $B_1$  and  $B_2$ . The individuals are numbered so that  $B_1 < B_2$  and  $x_1 > x_2$ . The approximate formula is then,

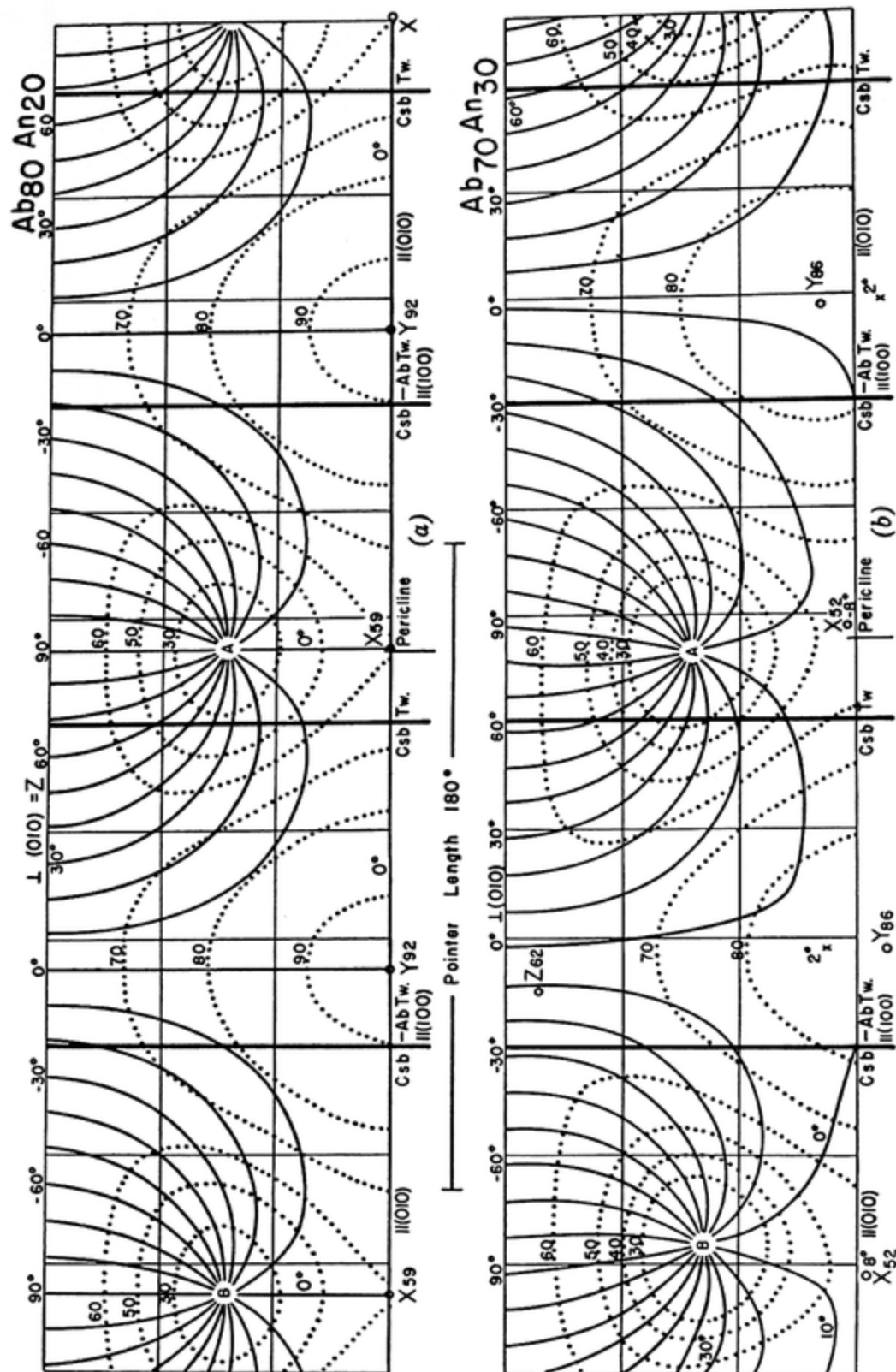
$$\log \left( \frac{B_2}{B_1} \right) = \log \left( \frac{\sin 2x_1}{\sin 2x_2} \right) = \log \sin 2x_1 - \log \sin 2x_2$$

This formula is correct only to the extent that the ratio of two angles equals the ratio of their sines; it is sufficiently accurate only if the larger retardation  $B_2 \leq 100 \text{ m}\mu$

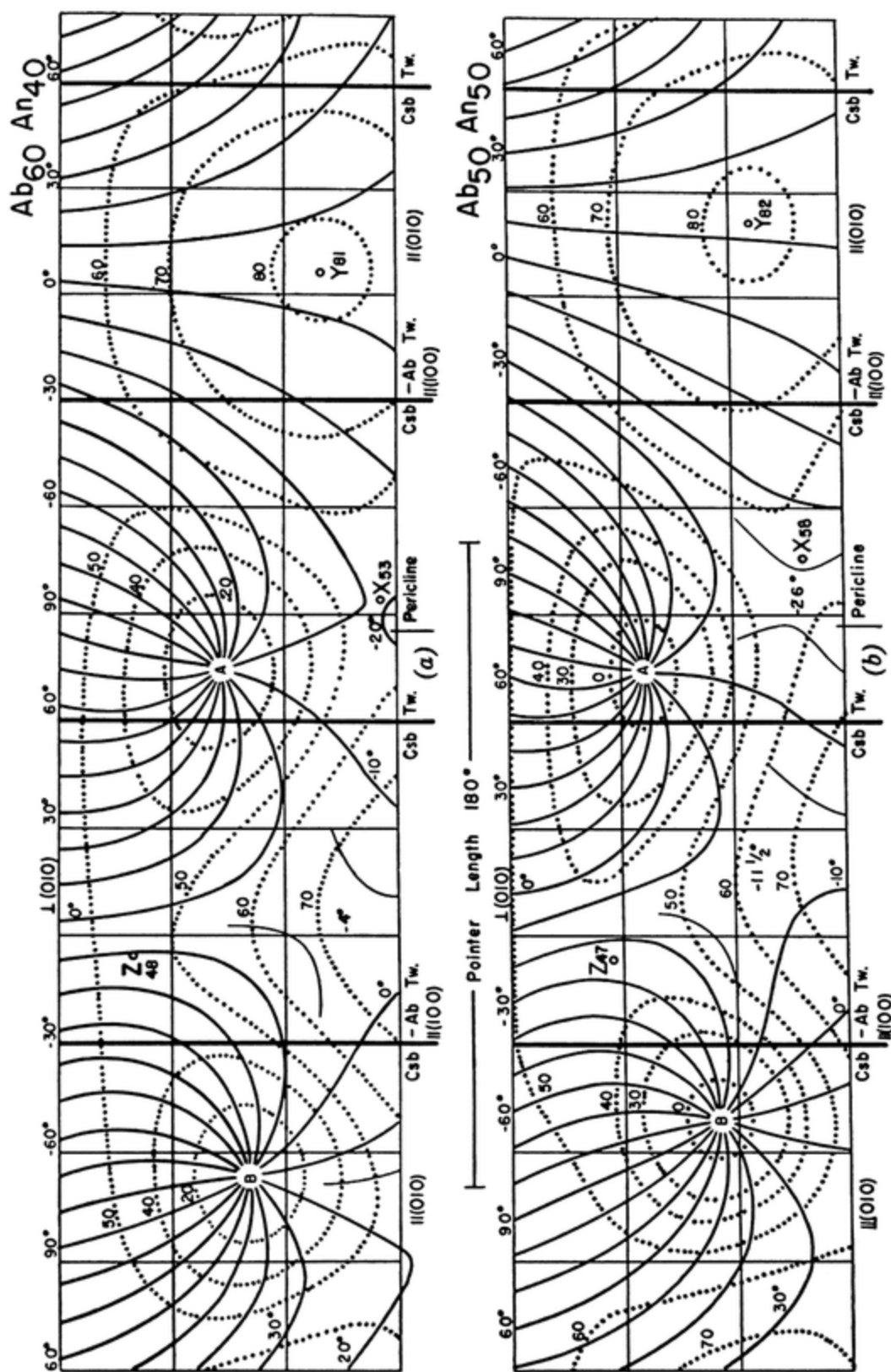
<sup>108a</sup> This notation differs from that of Nieuwenkamp, who uses  $R\Delta n$  for this ratio.



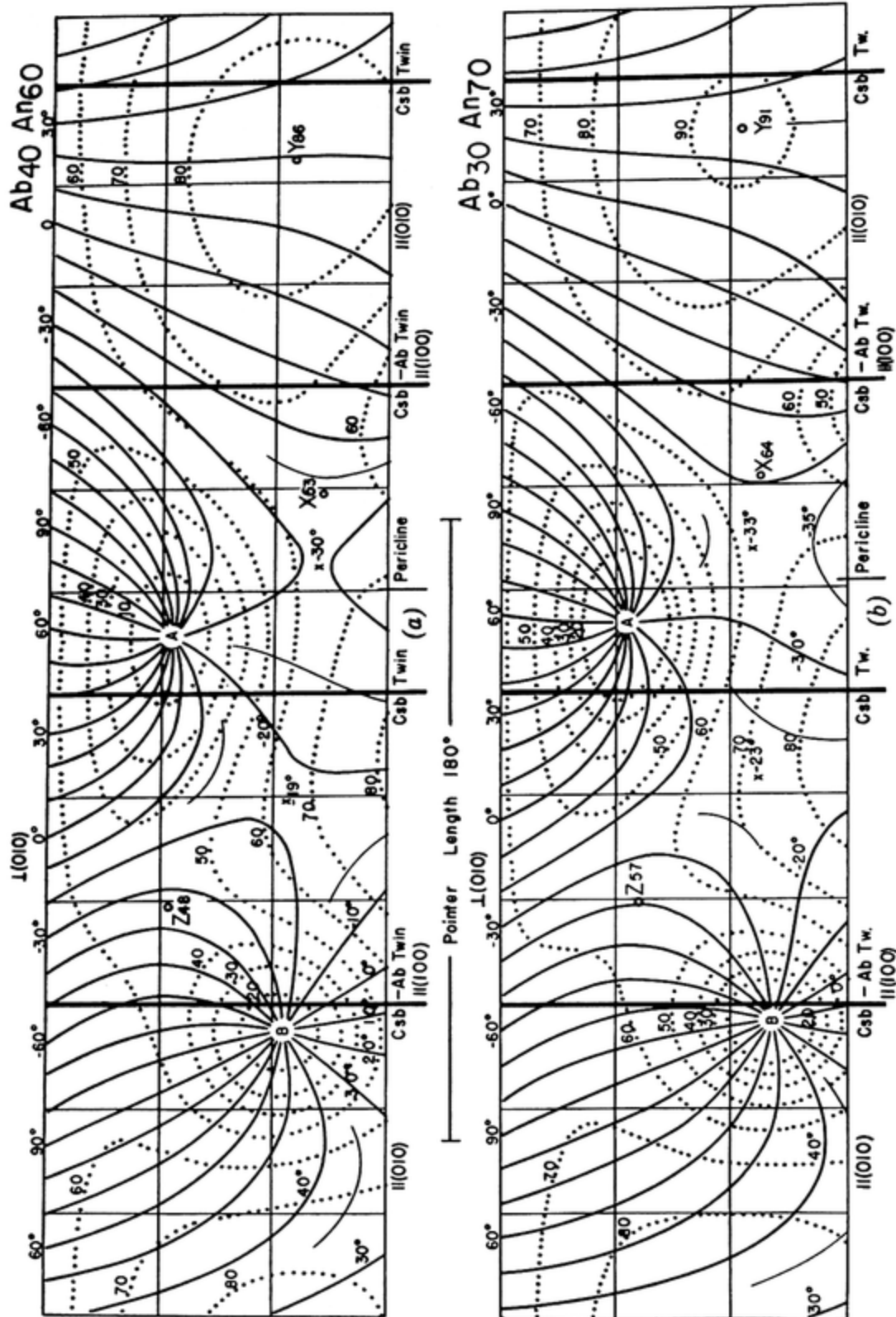




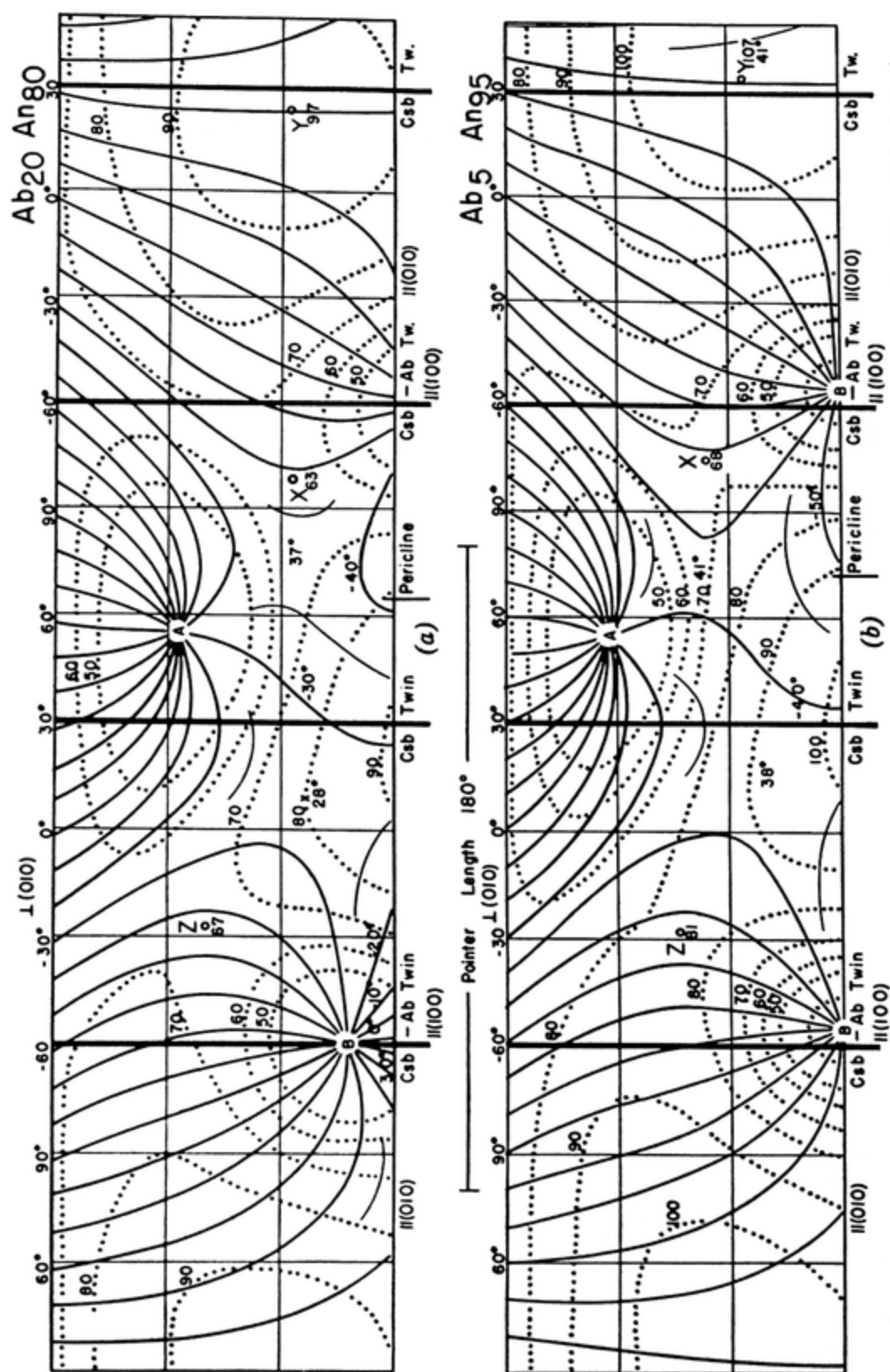
Figs. 219a, 219b. Optical properties of  $Ab_{80}An_{20}$  and of  $Ab_{70}An_{30}$ . Solid curves represent extinction angles  $X' \wedge 010$ ; dotted curves, logarithms of birefringence.



Figs. 220a, 220b. Optical properties of  $Ab_{60}An_{40}$  and of  $Ab_{50}An_{50}$ . Solid curves represent extinction angles  $X' \wedge 010$ ; dotted curves, logarithms of birefringence.



**Figs. 221a, 221b.** Optical properties of  $\text{Ab}_{40}\text{An}_{60}$  and of  $\text{Ab}_{30}\text{An}_{70}$ . Solid curves represent extinction angles  $X' \wedge 010$ ; dotted curves, logarithms of birefringence.



Figs. 222a, 222b. Optical properties of  $Ab_{20}An_{80}$  and of  $Ab_5An_{95}$ . Solid curves represent extinction angles  $X' \wedge 010$ ; dotted curves, logarithms of birefringence.

(low gray, first order; between parallel nicols white, with no trace of brownish yellow) and if the angle  $x_1$  is not too small or too nearly equal to  $x_2$ . A nomogram supplied by Nieuwenkamp can be used with this type of observation (angles between equal illumination and extinction positions) to determine  $\log(B_2/B_1)$  in sections having interference colors up to red of the first order ( $\Delta_2 = 300 \text{ m}\mu$ ;  $\Delta_1 < \Delta_2$ ). (See footnote ‡, p. 329.) The use of a compensator is to be preferred.

The Berek compensator is furnished with instructions and a table of  $\log f(i)$  by the manufacturer. It accomplishes the exact compensation of the retardation due to the grain under observation by tilting a plate of calcite cut normal to  $c$ , so as to change the birefringence of the plate in the direction along which axial rays travel in the microscope. Two positions of tilt  $a$  and  $b$  produce exact compensation in the grain under study, and one-half the difference of the readings of the compensator drum for these two positions  $\frac{a-b}{2}$  is the angle of tilt,  $i$ , of the calcite plate required to compensate exactly the retardation produced by the grain. This angle ( $i$ ) is obtained for each part of the twin, and in the manufacturer's direction booklet the values  $\log f(i_1)$  and  $\log f(i_2)$  are found, corresponding to  $i_1$  and  $i_2$ . The logarithmic birefringence-ratio,  $\log B_2/B_1$ , equals the difference between these values:

$$\log \frac{B_2}{B_1} = \log f(i_2) - \log f(i_1)$$

The sign of an extinction angle is rarely or never obtainable, but when the two extinction angles of a twin are measured, it is always possible to observe whether their signs are alike or different, and to note also which extinction angle is associated with the lamella of higher birefringence (smaller  $x$  or larger  $i$ ). If these important observations are applied in using the charts, there will generally be not more than two possible solutions, and commonly only one. In Carlsbad twins, 010 is the composition plane, but the two individuals are symmetrically related with respect to a plane normal to the  $c$ -axis; in Carlsbad-albite complex twins the composition plane is still 010, but the two individuals are related with respect to a plane parallel to  $c$  and normal to 010. The traces of these two twinning planes (not composition faces) are shown in Figs. 218a-222b by heavy vertical lines; orientations of light rays traversing sections through such twins are symmetrically located on opposite sides of the heavy lines. Two pointers placed with their four ends symmetrical to these lines will therefore show the optical properties of all four possible orientations of a combined Carlsbad-albite twin.

Pericline and various other types of twins may be treated systematically, using these charts with auxiliary ones provided by Nieuwenkamp. For additional charts and methods, the student is referred to the original.

A systematic ambiguity occurs for albite twins in two cases: first, if the anorthite content is less than about 40%; and second, if the section of the twin is exactly normal to 010. In the first case, determinations on albite twins alone lead to two possible compositions,  $(20+x)\%$  and  $(20-x)\%$  anorthite; relief or refractive indices, an interference figure, extinction angles in another lamella twinned according to a different law, the position of the 001 cleavage, or some other observation, will usually make possible the distinction between these two possibilities. In the second case, 010 normal to the section, only one extinction angle is obtained; Nieuwenkamp's method is useless, but other methods may be applicable, as for example that of Duparc and Reinhard, Fig. 182. Nieuwenkamp's method is of special interest when for any reason it is impossible or inconvenient to find a grain

with a recognizable orientation. The tabulated example will help to clarify the procedure for a simple albite twin.

### Observations

Microscope stage readings			Berek compensator readings		
Lamella	(1)	(2)		(1)	(2)
1. Extinction	98	48	6. Higher reading	33.8	35.2
2. Twin plane	78		7. Lower reading	25.6	23.8
3. Equal illumination *	63		8. Difference	8.2	11.4
4. Lamella <u>2</u> shows higher retardation. Its interference color with crossed nicols is * <u>gray</u> ; with parallel nicols is * <u>pale yellow</u> .					
5. Twinning plane is $\frac{\text{more}}{\text{less}} \checkmark$ than $30^\circ$ from vertical to the section.					

### Extinction angles

1-2 (1) +20; (2) -30; signs are  $\frac{\text{alike}}{\text{unlike}} \checkmark$ .

### Logarithm of ( $B_2/B_1$ )

Either (a), from equal illumination: *		Or (b), from compensator readings:	
$x_1 = I_1 - S$	<u>35</u> ; $\log \sin 2x_1$ <u>9.973</u>	$i_2 = \frac{S_2}{2} =$	<u>5.7</u> ; $\log f(i_2) \dagger$ <u>7.995</u>
$x_2 = S - I_2$	<u>15</u> ; $\log \sin 2x_2$ <u>9.699</u>	$i_1 = \frac{S_1}{2} =$	<u>4.1</u> ; $\log f(i_1) \dagger$ <u>7.709</u>
Diff. = approx. $\log (B_2/B_1) =$	<u>.274</u>	Exact $\log (B_2/B_1) =$	<u>.286</u>
Plus correction if necessary $\ddagger$	<u>.01</u>	Result to nearest .01	<u>.28+</u>
Exact $\log (B_2/B_1) =$	<u>.28</u>	For use on charts	<u>28.</u>

### Chart readings of $\log (B_2/B_1)$ for various coincidences of extinction angles:

An(0)	An(10)	An(20)	An(30)	An(40)	An(50)	An(60)	An(70)	An(80)	An(95)
61	Large	.....	20	10	19	33	38	40	46
33	25		Large	Large	Large	51	50	35	30

Charts show inclination  $>30^\circ$ ; eliminated by  $\checkmark$ .

Observed value 28 falls between 19 and 33. Interpolate for result.

**Conclusion:** Anorthite content 57 %

The sequence of observations is apparent from the table. In ordinary practice, either the compensator readings or the equal illumination readings (starred in the table) will be used, but not both as was done here for illustration. Observation 5, having to do with the approximate inclination of the twin composition plane, may

\* Unnecessary if compensator is used.  $\log \sin 2x$  from any log tables or from an ordinary slide rule. Italic numbers refer to observations above:  $I_1 - S = 98 - 63 = 35$ .

$\dagger$  From Table I of directions pamphlet supplied with Berek compensator.

$\ddagger$  See bottom of opposite page.



be needed to eliminate one or more otherwise possible coincidences of observed data with chart data. In the example here used, it eliminated the compositions An(8) and An(28). This estimate of the inclination of the composition plane is made easily by observing the apparent movement of the shadowy boundary between the lamellae as the microscope stage is rotated from one extinction position to another; the narrowness of that boundary at certain positions of equal illumination is also an excellent indication of its orientation.

The setting of the microscope stage for equal illumination of the two parts of the twin must be made with care, for even a small error in this setting may sometimes result in considerable error in the calculated value of  $\log(B_2/B_1)$ . Improved accuracy may be obtained by using all eight of the positions of equal illumination, together with the four positions of extinction in each part of the twin. Denoting the two lamellae by subscripts, and distinguishing the four positions of equal illumination lying between unlike vibration directions ( $X'$  and  $Z'$ ) in the two parts by a prime mark, we obtain four values each for  $x_1$ ,  $x_2$ ,  $x_1'$ , and  $x_2'$ ; these are averaged, and the two pairs of averages ( $x_1$ ,  $x_2$ ) and ( $x_1'$ ,  $x_2'$ ) are used independently in the calculation of the logarithm of  $B_2/B_1$  under (a) in the table. The two results should be the same, or, if slightly different, that one should be given more weight which is derived from the larger  $x$  values.

‡ The following table shows corrections to be added for various values of retardation (interference color) and of  $\log(B_2/B_1)$ :

Retardation, $m\mu$				Approximate log ( $B_2/B_1$ )						
Color, Parallel Nicols	Color, Crossed Nicols, with Sensi- tive Tint Plate		Absolute Retarda- tion	.10	.20	.30	.40	.50	.60	.70
	Retardation			Corrections to Add						
	De- creased	In- creased								
White	Golden yellow	Light blue	100	.01	.01	.01	.02	.02	.02	.02
Cream yellow	Lemon yellow	Pale blue	150	.02	.03	.04	.04	.04	.04	.04
Golden yellow	Cream yellow	Yellow- green	200	.04	.06	.07	.08	.08	.08	.08
Red	Cream white	Green- yellow	250	.08	.11	.12	.12	.13	.13	.13

The optical orientation of plagioclase changes <sup>109</sup> a small but measurable amount on heating; also, the optical orientation of plagioclase in volcanic rocks differs a little from that of plagioclase in plutonic rocks, pegmatites, and schists.

**ALTER.** Plagioclase alters in many different ways under varying conditions (see pages 276–279), but the change to sericite is especially common. The alteration to kaolinite and other minerals of clay is also very common, while saussuritization of calcic plagioclase is widespread under certain conditions. Less common products of alteration include zeolites, calcite, prehnite, wollastonite, topaz, etc.

**OCCUR.** Plagioclase is one of the commonest minerals of the earth's crust. It is a minor constituent of granite and an essential abundant constituent of gabbro, diorite, basalt, etc. One type (albite) is common in pegmatites and veins; the same one is abundant in many schists and gneisses. Both residual and regenerated plagioclases are not rare in sedimentary rocks. Bytownite is the rarest type.

**DIAG.** See pages 279–296, 317–329 and Figs. 148, 170–176, 182–187, as well as data on optic properties given on pages 313–317.

#### (a) WITHOUT ADDITIONAL ANIONS—HYDROUS ZEOLITES

The zeolites are silicates of aluminum and another base, containing water, which can be expelled without destroying the crystal. The zeolites are closely related in composition, but they are quite diverse in crystal habit and symmetry. Two zeolites (analcite and faujasite) are isometric, one (ashcroftine) is tetragonal, three (chabazite, gmelinite, and levynite) are (nearly) rhombohedral, several (thomsonite, natrolite, gismondite, edingtonite, gonnardite, epidesmine, etc.) are orthorhombic, and all the rest are monoclinic (unless mesolite and pseudomesolite are triclinic?).

**COMP.** Zeolites vary in composition in the same way as do the feldspars; <sup>110</sup> that is, CaAl is replaced by NaSi. Doubtless because of the expanded crystal structure, they also vary (usually to a minor extent) under control of valence, so that Ca is replaced by Na<sub>2</sub>, but this variation is perhaps secondary in origin. The relations in composition among the more important zeolites are shown diagrammatically in Fig. 223.

**PHYS. CHAR.** Many zeolites are fibrous to columnar; a few are equant rhombohedral, pyramidal, or octahedral. Hardness and specific gravity

<sup>109</sup> A. Köhler: *Tsch. Min. Pet. Mit.*, LIII, 24 and 159 (1941); H. Tertsch: *Cent. Min.*, A, 1942, 137.

<sup>110</sup> A. N. Winchell: *Am. Mineral.*, X, 88, 112, 145 (1925).

are distinctly less than those of corresponding anhydrous silicates;  $H. = 3.5-5.5$ .  $G. = 2-2.4$  (rarely 2.7 *ca*). Decomposed by acid, usually with gelatinization. Readily fusible, mostly with intumescence.

**OPT. PROP.** Zeolites have low refringence and negative relief; with few exceptions (especially thomsonite) they have weak (even zero) birefringence. They are white or colorless except when stained by impurities.

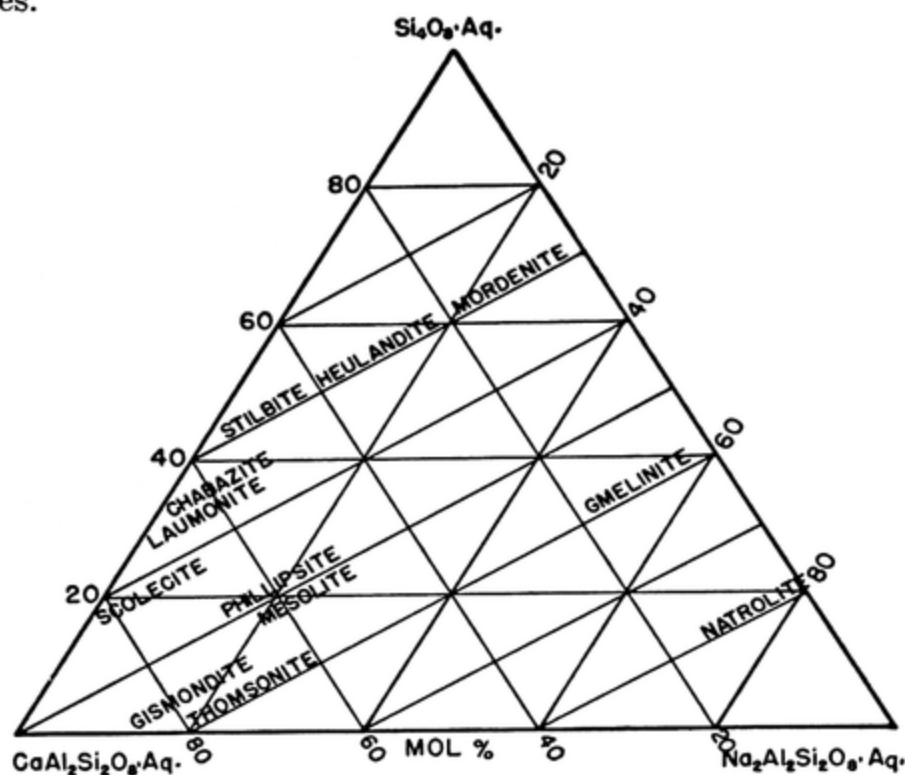


FIG. 223. Relations in composition of the zeolites.

**ALTER.** Being themselves possible alteration products, zeolites do not easily change to other minerals, but sometimes they have been observed to alter to kaolinite, or to calcite, or to an isotropic substance. Under other conditions they may be transformed to feldspar or prehnite.

**OCCUR.** Zeolites are nearly always secondary minerals formed by the hydration of aluminum silicates of calcium, sodium, etc. They are derived chiefly from feldspars, but also from nepheline, leucite, sodalite, etc. They are found commonly in amygdaloidal cavities, fractures, or veins in rocks of many types, especially in basic igneous rocks. They occur also in veins, deposits of hot springs, and even on the ocean bottom. They are often associated with calcite, prehnite, pectolite, apophyllite, datolite.

**DIAG.** As compared with other silicates zeolites are characterized by low refringence, weak birefringence, inferior hardness, low specific

gravity, lack of color, abundant tenor of water, and occurrence as secondary products; most of them are fibrous.

*Analcite* and *faujasite* are easily distinguished from all other zeolites by their isotropic character; *chabazite*, *gmelinite*, and *levynite* are similar in having very weak birefringence; they have a variable but small (to zero) optic angle. *Gismondite* has a large optic angle of negative sign with  $N_Z - N_X = 0.008$ ; its external form is that of a tetragonal bi-

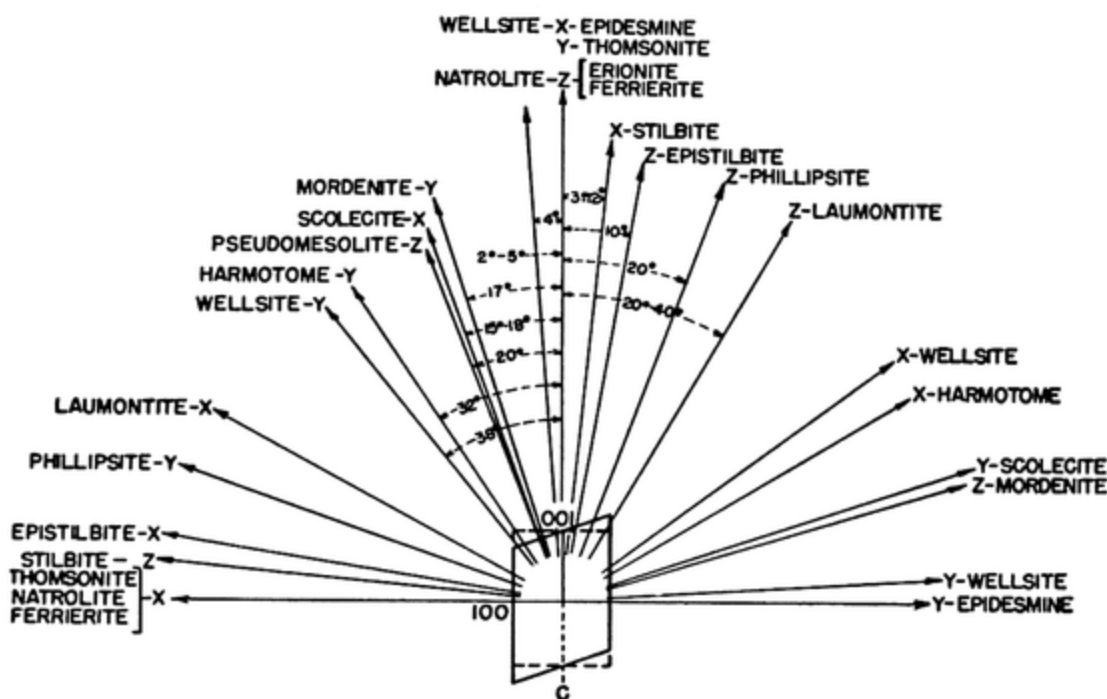


FIG. 224. The optic orientation of fibrous and columnar zeolites.

pyramid composed of monoclinic units, complexly twinned. *Heulandite* and *brewsterite* are usually flattened parallel to the perfect 010 cleavage with more or less vertical elongation. Both have the positive acute bisectrix normal to the cleavage whose direction is therefore negative. *Edingtonite* has a large positive optic angle; crystals are minute and apparently tetragonal pyramids.

All other zeolites are fibrous and may be divided into three groups according as the elongation is positive,  $\pm$ , or negative.

Those with positive elongation have maximum extinction angles, as measured on that direction, as follows: erionite  $0^\circ$ , natrolite  $0^\circ$ , ashcroftine  $0^\circ$ , epistilbite  $9^\circ$ , pseudomesolite  $20^\circ$ , phillipsite  $11^\circ$ – $30^\circ$ , laumontite  $25^\circ$ – $30^\circ$ .

Those with  $\pm$  elongation have maximum extinction angles as follows: thomsonite  $0^\circ$ , mesolite  $5^\circ$ , mordenite  $15^\circ$ , chlorastrolite  $20^\circ$ , harmotome  $28^\circ$ .

Those with negative elongation have maximum extinction angles as follows: wellsite  $2^\circ$ , stilbite  $5^\circ$ , scolecite  $15^\circ$ .

The optic orientation of fibrous zeolites as seen in section parallel to 010 is shown in Fig. 224.

**ANALCITE** <sup>111</sup> (*Analcime*) ISOMETRIC HEXOCTAHEDRAL <sup>112</sup>  $NaSi_2AlO_6 \cdot H_2O$

COMP. Often contains excess  $SiO_2$  and  $H_2O$  apparently as  $SiSi_2O_6 \cdot 2H_2O$  in crystal solution; also excess <sup>113</sup>  $Al_2O_3$  (as  $NaSiAl_2O_5(OH) \cdot H_2O?$ ); also may contain minor  $K_2O$ ,  $CaO$ , etc.

STRUC. Space group <sup>112</sup>  $Ia\bar{3}d$ ;  $a$  13.68 Å. U.C. 16.

PHYS. CHAR. Crystals often trapezohedral or more complex. Penetration twinning common. Very poor 001 cleavage.  $H. = 5-5.5$ .  $G. = 2.22-2.29$ .  $F. = 2.5$  to colorless glass. Gelatinizes with HCl.

OPT. PROP. Usually isotropic with  $N = 1.479-1.489$ ; large crystals often very weakly birefringent <sup>114</sup> with complicated twinning and  $(- )2V =$  small to large;  $N = 1.487$ ,  $N_z - N_x = 0.001$ .

Colorless, white, gray, greenish. Colorless in thin section.

OCCUR. Analcite is usually a secondary mineral, often associated with other zeolites; it may be an alteration product of nepheline or sodalite. Rarely it is a primary constituent of volcanic rocks, easily mistaken for leucite.

DIAG. Analcite is distinguished by its very low refringence and its nearly or quite isotropic character. It differs from sodalite by the absence of color, often present in sodalite, and different cleavage; it differs from leucite in the absence of regularly arranged inclusions, common in leucite, and lower refringence; it has higher refringence than opal and distinctly lower index than ordinary glass. Chemical tests may be needed to identify it with certainty.

*Apoanalcite* <sup>115</sup> seems to be analcite with about 57 mol. per cent of  $NaSiAl_2O_5(OH) \cdot H_2O$ . It is uniaxial positive with  $N_o = 1.475$ ,  $N_e = 1.487$ ,  $N_e - N_o = 0.012$ . But the dehydration curve is not like that of a zeolite.

**FAUJASITE** ISOMETRIC HEXOCTAHEDRAL <sup>115, 116</sup>  $Na_2CaSi_{10}Al_4O_{28} \cdot 20H_2O?$

PHYS. CHAR. Crystals octahedral; twinning on 111. Distinct 111 cleavage.  $H. = 5$ .  $G. = 1.92$ .  $F. = 3$ . Decomposed by acid.

OPT. PROP. Isotropic with  $N = 1.48$ . Loss of a little water changes it to anisotropic, uniaxial, positive, with  $N = 1.48$  ca. and weak birefringence, the octahedron then consisting of eight pyramidal segments each having an octahedral face for the base and an optic axis normal thereto; the birefringence decreases on warming (even in warm balsam), and at about  $150^\circ$  (having lost  $12H_2O$ ) the mineral is again isotropic. Further heating changes it to uniaxial, negative. Upon cooling in damp air, the water is taken up again and the optic changes reversed.

<sup>111</sup> In spite of containing zeolitic water analcite is related to pollucite.

<sup>112</sup> J. W. Gruner: *Zeit. Krist.*, LXVIII, 365 (1928).

<sup>113</sup> C. Oftedahl: *Norsk Geol. Tidsk.*, XXVI, 215 (1947).

<sup>114</sup> For a discussion of the birefringence of analcite see F. H. Stewart: *Mineral. Mag.*, XXVI, 1 (1941).

<sup>115</sup> H. Neumann: *Norsk. Geol. Tidsk.*, XXVII, 171 (1949).

<sup>116</sup> W. Witteborg: *Zeit. Krist.*, LXXXIII, 374 (1932).

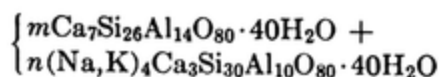
Colorless, white, or stained by impurities; colorless in thin section.

**OCCUR.** Faujasite is found with augite in limburgite in Baden, etc.

**DIAG.** Faujasite differs from other zeolites in its isotropic character.

**Ashcroftite** <sup>117</sup>  $[\text{NaK}(\text{Ca}, \text{Mg}, \text{Mn})\text{Si}_5\text{Al}_4\text{O}_{18} \cdot 8\text{H}_2\text{O}]$  is tetragonal with  $c/a = 0.514$ . Space group  $P4/mnm$ ;  $a$  34.04,  $c$  17.49 Å. U.C. 40. Crystals fibrous prismatic with perfect 100 and distinct 001 cleavages.  $G = 2.61$ . Uniaxial positive with  $N_O = 1.536$ ,  $N_E = 1.545$ ,  $N_E - N_O = 0.009$ . Found as a pink powder in cavities in augite syenite in Greenland. **Falkensteinite** <sup>118</sup> is similar, but is more siliceous and is uniaxial negative with  $N_O = 1.508$ ,  $N_E = 1.505$ .

**CHABAZITE** HEXAGONAL SCALENOHEDRAL  
 $c/a = 1.086$



(Monoclinic  $a:b:c = 0.463:1:0.341$   $\beta = 96^\circ 29'$ )

**COMP.** Chabazite varies notably in composition, about as indicated above, but the variations have been explained in other ways by Tschermak,<sup>119</sup> Groth,<sup>120</sup> and others.

**STRUC.** Space group <sup>121</sup>  $R\bar{3}m$ ;  $a$  13.75,  $c$  14.94 Å. Unit cell contains 24 oxygen atoms.

**PHYS. CHAR.** Crystals often simple rhombohedrons resembling a cube since the rhombohedral angle is  $85^\circ 14'$ ; also more complex, or {0001} tablets. Penetration

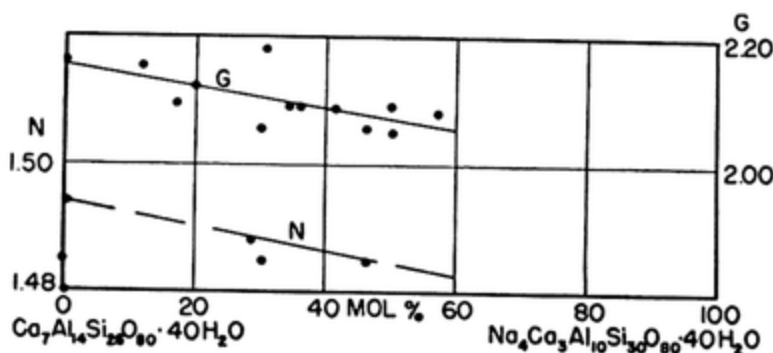


FIG. 225. Properties of chabazite.

twins on 0001. Distinct rhombohedral cleavage.  $H. = 4-5$ .  $G. = 2.08-2.16$ . See Fig. 225.  $F. = 3$  with intumescence. Decomposed by  $\text{HCl}$ .

**OPT. PROP.** Chabazite crystals are usually biaxial, basal sections being divided into six sectors of varying extinction with the optic planes in different positions. The units are probably triclinic (or monoclinic), and the rhombohedral external form is the result of twinning on 110 and  $1\bar{1}0$ ; the "rhombohedral" cleavage is considered to be actually cleavage parallel to 001, 100, and 010 of the triclinic (or monoclinic)

<sup>117</sup> Formerly *kalithomsonite*. See S. G. Gordon: *Proc. Phila. Acad. Sci.*, LXXVI, 261 (1924); M. H. Hey and F. A. Bannister: *Mineral. Mag.*, XXIII, 305 (1933).

<sup>118</sup> T. F. W. Barth: *Min. Abst.*, X, 5 (1947).

<sup>119</sup> G. Tschermak: *Sitzb. Akad. Wiss. Wien*, CXXVI, 541 (1917), and CXXVII, 177 (1918).

<sup>120</sup> P. Groth: *Mineral. Tabellen*, 1921, 124.

<sup>121</sup> J. Wyart: *C. R. Acad. Sci. Paris*, CXCI, 1244 (1931); *Min. Abst.*, V, 162 (1932).



unit. Some crystals are strictly uniaxial; others are uniaxial in some parts and biaxial in others. The optic angle is variable, but small. The sign is negative in some crystals and positive in others. These peculiarities have been explained in three different ways: (1) according to Brauns<sup>122</sup> the component molecules of chabazite are  $CaAl_2Si_6O_{16} \cdot 8H_2O$  and  $Ca_2Al_4Si_4O_{16} \cdot 8H_2O$  and the first is positive while the second is negative; (2) according to Pirsson<sup>123</sup> chabazite and gmelinite form a series and chabazite is positive while gmelinite is negative; (3) according to Rinne<sup>124</sup> fully hydrated chabazites are positive, slight heating changes them to negative, and further heating changes them back to the positive condition but with strong birefringence.

$(\pm)2V = 0^\circ-32^\circ$ ,  $N_X = 1.478-1.485$ ,  $N_Y = ?$ ,  $N_Z = 1.480-1.490$ ,  $N_Z - N_X = 0.002-0.010$ , usually very weak. See Fig. 225.

Color white or pink; colorless in thin section.

Chabazite is remarkable even among the zeolites for its ability to change the tenor of  $H_2O$ , and also the tenor of  $Na_2$  in place of  $Ca$ , without destroying the crystal.

**OCCUR.** Chabazite is found in cavities in volcanic rocks often associated with phillipsite; also in fractures in crystalline limestones and schists with stilbite, laumontite, etc.; also abundant as a recent deposit of certain hot springs.

**DIAG.** Chabazite differs from gmelinite in composition and cleavage, and from other zeolites in external crystal form, very weak birefringence and small optic angle.

<b>GMELINITE</b>	HEXAGONAL SCALENOHEDRAL	$\{ mNa_{12}Si_{28}Al_{12}O_{80} \cdot 40H_2O +$
	$c/a = 1.017$	$\{ nNa_{10}Ca_2Si_{26}Al_{14}O_{80} \cdot 40H_2O$

(Monoclinic  $a:b:c = 0.457:1:0.399$   $\beta = 97^\circ 37'$ )

**COMP.** Gmelinite varies much in composition, in part by (secondary?) substitution of  $Ca$  for  $Na_2$ , grading toward chabazite, and these variations have been explained like those of chabazite.

**PHYS. CHAR.** Crystals hexagonal or rhombohedral with vertical striations; penetration twins on 001 (or  $10\bar{1}1$ ). Distinct prismatic cleavage and basal parting.  $H. = 4.5$ .  $G. = 2.04-2.17$ .  $F. = 3$  with intumescence. Decomposed by  $HCl$ .

**OPT. PROP.** Similar to chabazite in all respects. According to Grandjean,<sup>125</sup> anhydrous gmelinite is uniaxial positive with  $N_E - N_O = 0.027$ . Ordinary gmelinite<sup>126</sup> has  $(\pm)2V = \text{small}$ ,  $N_X = 1.464-1.479$ ,  $N_Y = ?$ ,  $N_Z = 1.465-1.480$ ,  $N_Z - N_X = 0.001-0.009$ , usually very weak.

Colorless, white, or tinted by impurities. Colorless in thin section.

**OCCUR.** Gmelinite is found in amygdules at Glenarm, Ireland; Bergen Hill, New Jersey, etc.

**DIAG.** Gmelinite differs from chabazite in composition and cleavage and from other zeolites in external form, very weak birefringence, and small optic angle.

**Levynite** ( $Ca_8Si_{24}Al_{16}O_{80} \cdot 40H_2O$ ) is rhombohedral with  $c/a = 0.836$ . It often contains a little  $Na$  and  $K$ .  $H. = 4-4.5$ .  $G. = 2.09-2.16$ . Easily fusible. Uniaxial negative with  $N_O = 1.496$ ,  $N_E = 1.491$ ,  $N_O - N_E = 0.005$ . Colorless or tinted

<sup>122</sup> R. Brauns: *Optische Anomalien*, Leipzig, 1891.

<sup>123</sup> L. V. Pirsson: *Am. Jour. Sci.*, CXLII, 57 (1891).

<sup>124</sup> F. Rinne: *Sitzb. Akad. Wiss. Berlin*, 1890, 1163.

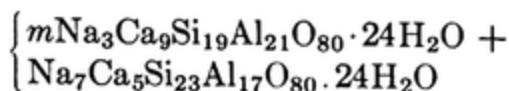
<sup>125</sup> F. Grandjean: *C. R. Acad. Sci. Paris*, CXLIX, 866 (1909); *Bull. Soc. Fr. Min.*, XXXIII, 5 (1900).

<sup>126</sup> Optic sign is negative: J. Mélon and J. D. H. Donnay: *Ann. Soc. Géol. Belg.*, LIX, B, 162 (1935-1936).

reddish or yellowish by impurities. Found in amygdules in basalt, as at Table Mountain, Colorado.

**Arduinite** ( $m\text{Na}_7\text{Ca}_5\text{Si}_{23}\text{Al}_{17}\text{O}_{80}\cdot 29\text{H}_2\text{O} + n\text{Na}_8\text{Ca}_4\text{Si}_{24}\text{Al}_{16}\text{O}_{80}\cdot 29\text{H}_2\text{O}$ ) is orthorhombic(?). Crystals form fibrous radiating aggregates.  $G. = 2.26$ . The optic plane is parallel with the cleavage.  $(+ )2V = \text{nearly } 90^\circ$ ,  $N_X = 1.474$ ,  $N_Y = 1.476$ ,  $N_Z = 1.478$ ,  $N_Z - N_X = 0.004$ . Stained red by iron. Found in cavities in basic igneous rocks in Venetia, Italy.

## THOMSONITE



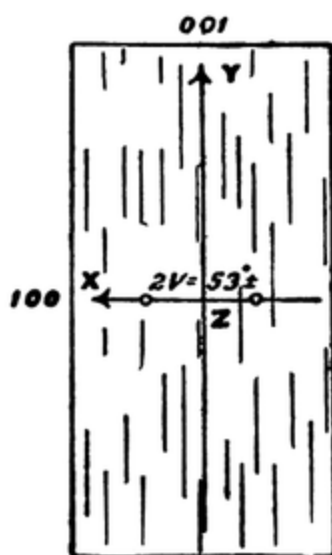
ORTHORHOMBIC PYRAMIDAL

$$a:b:c = 0.993:1:1.007$$

**COMP.** Besides the series shown above there may be a little replacement of Ca by  $\text{Na}_2$  (secondary?).

**STRUC.** Space group <sup>127</sup>  $Pnn$ ;  $a$  13.04,  $b$  13.06,  $c$  13.22 Å. U.C. 1.

**PHYS. CHAR.** Euhedral crystals rare; habit prismatic to fibrous, vertically striated. Commonly lamellar parallel to 010; often radiated. Perfect 010 and poor 100 cleavages.  $H. = 5-5.5$ .  $G. = 2.25-2.40$ .  $F. = 2$  with intumescence. Gelatinizes with HCl.



**OPT. PROP.** The optic plane is 001 (normal to elongation);  $Z = b$ . See Fig. 226.  $(+ )2V = 47^\circ-75^\circ$  *ca.*,  $r > v$  distinct.  $N_X = 1.511-1.530$ ,  $N_Y = 1.513-1.532$ ,  $N_Z = 1.518-1.545$ ,  $N_Z - N_X = 0.006-0.020$ ;  $F - C$  for  $N_Y = 0.0074$ . Variations in optic properties with variations in composition are shown in Fig. 227. As suggested in the figure, thomsonite rich in Si and Na may be negative.

Reducing the tenor of water from  $24\text{H}_2\text{O}$  to  $16\text{H}_2\text{O}$  lowers the refringence about 0.025, as shown in Fig. 228.

FIG. 226. The optic orientation of thomsonite.

Colorless, white, yellow, pink. Colorless in thin section.

**INVER.** When thomsonite is heated it loses water and at the same time the indices of refraction decrease about 0.01 for each  $100^\circ$  up to  $300^\circ$ . Thomsonite undergoes a readily reversible inversion <sup>128</sup> at a temperature which varies with the composition, being about  $290^\circ$  for  $\text{Na}_4\text{Ca}_8\text{Al}_{20}\text{Si}_{20}\text{O}_{80}\cdot 24\text{H}_2\text{O}$  and about  $170^\circ$  for  $\text{Na}_5\text{Ca}_7\text{Al}_{19}\text{Si}_{21}\text{O}_{80}$

<sup>127</sup> W. H. Taylor, C. A. Meek, and W. W. Jackson: *Zeit. Krist.*, LXXXIV, 373 (1933).

<sup>128</sup> M. H. Hey: *Mineral. Mag.*, XXIII, 51 (1932).

$\cdot 24H_2O$ . The high-temperature phase (*metathomsonite*) has the optic plane parallel with 100. *Gonnardite* may be merely *metathomsonite*<sup>128</sup> stable at ordinary temperature because rich in silica and soda.

**OCCUR.** Thomsonite is closely associated with other zeolites or prehnite in cavities in basic igneous rocks, schists, or contact rocks.

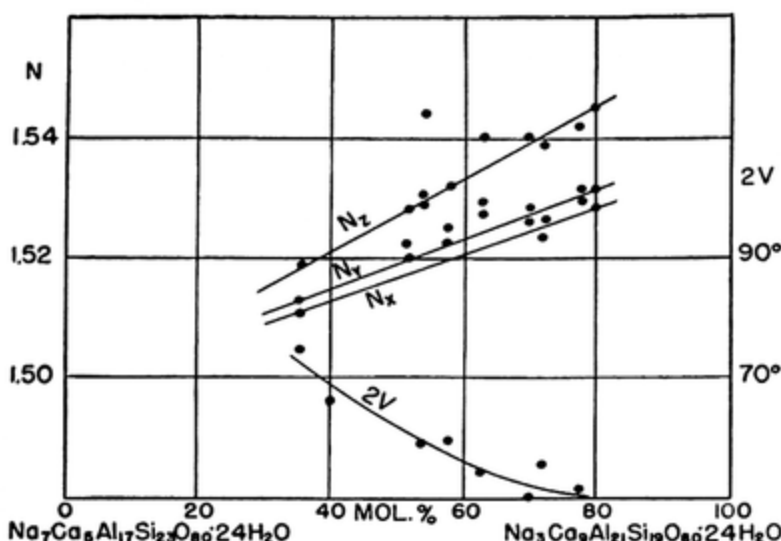


FIG. 227. Properties of thomsonite. See M. H. Hey: *Mineral. Mag.*, XXIII, 51 (1932).

**DIAG.** Thomsonite is characterized among zeolites by its parallel extinction and  $\pm$  sign of elongation.

**Gonnardite** ( $Na_3Ca_4Si_{24}Al_{16}O_{80} \cdot 28H_2O$ ?) is orthorhombic<sup>128</sup> with  $a:b:c = 1.00:1.0498$ .  $a$  13.35,  $b$  13.35,  $c$  6.65. Usually fibrous with  $H. = 4.5-5$ .  $G. = 2.19$ .  $F. =$  easy with swelling. Gelatinizes with  $HCl$ . Natural flattening or cleavage normal to  $X$ ;  $Z = c =$  elongation (Lacroix<sup>129</sup>).  $X = c =$  elongation (Hey<sup>128</sup>).  $(- )2V =$  small,  $N = 1.508$ ,  $N_Z - N_X = 0.002$  (Hey<sup>128</sup>). Perhaps the same as *metathomsonite* rich in silica. Color white. Alters to a zeolite with negative elongation or to thomsonite. Found in cavities in basalt at Gignat, France.

**Erionite**<sup>130</sup> ( $NaKC aSi_{12}Al_4O_{32} \cdot 12H_2O$ ?) is orthorhombic and fibrous like wool.  $G. = 2.0$ .  $F. =$  easy to clear glass. Soluble in  $HCl$ .  $Z = c$  (elongation).  $(+)2V = ?$ ,  $N_X = 1.438$ ,  $N_Y = 1.44$ ,  $N_Z = 1.452$ ,  $N_Z - N_X = 0.014$ . Color white. Found in cavities in rhyolite in Oregon.

**Ferrierite**<sup>131</sup> ( $Na_4Mg_2Si_{32}Al_8O_{80} \cdot 20H_2O$ ?) is orthorhombic in 100 laths with vertical elongation. Perfect 100 cleavage.  $H. = 3-3.5$ .  $G. = 2.15$ .  $F. = 3-3.5$ . Whitens in closed tube. Nearly insoluble in  $HCl$ . The optic plane is 010 and  $Z = c$ .  $(+)2V = 50^\circ 25'$ ,  $N_X = 1.478$ ,  $N_Y = 1.479$ ,  $N_Z = 1.482$ ,  $N_Z - N_X = 0.004$ . Colorless to white. Exceptional as a zeolite in containing magnesium. Found in veins with chalcedony in basalt at Kamloops Lake, British Columbia.

<sup>129</sup> A. Lacroix: *Bull. Soc. Fr. Min.*, XIX, 426 (1896).

<sup>130</sup> A. S. Eakle: *Am. Jour. Sci.*, VI, 66 (1898).

<sup>131</sup> R. P. D. Graham: *Trans. Roy. Soc. Canada*, XII, 185 (1918).

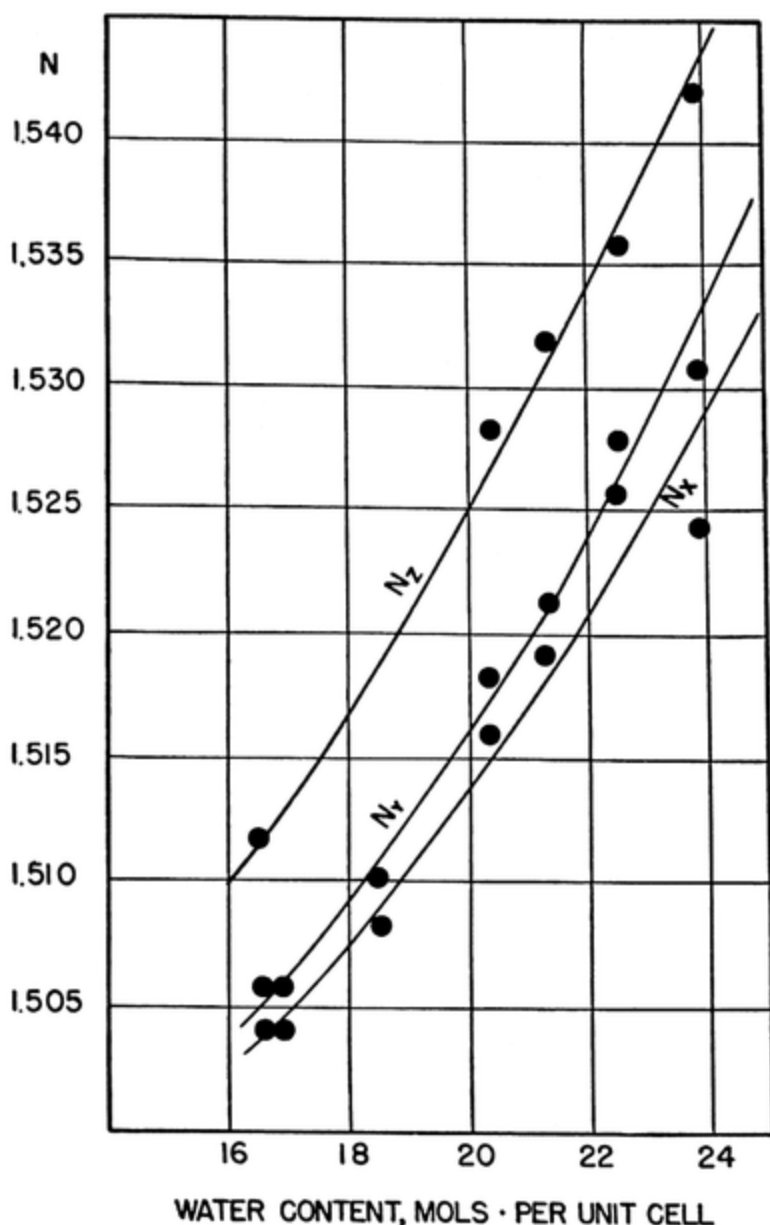


FIG. 228. Properties of thomsonite with varying tenor of  $H_2O$ . See M. H. Hey: *Mineral. Mag.*, XXIII, 51 (1932).

# EDINGTONITE

ORTHORHOMBIC DISPHENOIDAL



$$a:b:c = 0.987:1:0.673$$

COMP. Small amounts of Ca may replace Ba.

STRUC. Space group <sup>122</sup>  $P2_12_12$ ,  $a$  9.56,  $b$  9.68,  $c$  6.53 Å. U.C. 2.

PHYS. CHAR. Crystals minute pseudotetragonal with perfect 110 cleavage.  $H. = 4$ .  $G. = 2.7-2.78$ .  $F. = 5$ . Gelatinizes with acid.

OPT. PROP. The optic plane is 010;  $X = c$ . A sample <sup>122</sup> with only 0.10 CaO has  $(- )2V = 53^\circ 52'$ ,  $r < v$ ,  $N_X = 1.541$ ,  $N_Y = 1.553$ ,  $N_Z = 1.557$ ,  $N_Z - N_X = 0.016$ , while a crystal with about 6.0 CaO has  $(- )2E = 10^\circ - 15^\circ$ ,  $N_X = 1.542$ ,  $N_Y = 1.550$ ,  $N_Z = 1.550$ ,  $N_Z - N_X = 0.008$ .

<sup>122</sup> M. H. Hey: *Mineral. Mag.*, XXIII, 483 (1934).

From goniometric and X-ray measurements<sup>132</sup> the sample with about 6.0 CaO is tetragonal scalenohedral with  $a$  (and  $b$ ) 9.585,  $c$  6.53 Å.  $c/a$  0.681, space group  $P4_21m$ . Edingtonite with Ba artificially replaced in large part by Tl or Ag or Na or K is also apparently tetragonal.

Color white, grayish, pink. Colorless in thin section.

OCCUR. Edingtonite is found with thomsonite, analcite, etc., at the mines of Böhl, Sweden.

DIAG. Edingtonite has high refringence and birefringence for a zeolite; optic sign and sign of elongation negative; crystals minute, pyramidal.

**MORDENITE** ORTHORHOMBIC PYRAMIDAL(?)  $(Na,K)_4Ca_2Si_{40}Al_8O_{96} \cdot 28H_2O(?)$   
 $a:b:c = 0.896:1:0.369$

COMP. The ratio of Ca to  $(Na,K)_2$  seems to vary much; the tenor of  $H_2O$  is also variable. *Ptilolite* probably belongs to the mordenite series.

STRUC. Space group<sup>133</sup>  $Cmc$  or  $Cmcm$ ;  $a$  18.25,  $b$  20.35,  $c$  7.50 Å. U.C. 1.

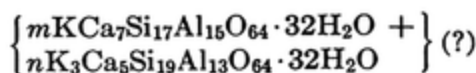
PHYS. CHAR. Crystals prismatic, vertically striated. Cottony aggregates. Perfect 100 and good 010 cleavages.  $H. = 5$ .  $G. = 2.1$ .  $F. = 3-4$  to clear glass. Insoluble in HCl.

OPT. PROP. Optically, monoclinic symmetry seems to be present ( $X \wedge c = 4^\circ$ ), though it cannot be detected by X-rays.  $Z = b$ . Optic angle large and variable, positive; also negative; <sup>134</sup>  $N_X = 1.471-1.478$ ,  $N_Y = 1.477$  ca.,  $N_Z = 1.473-1.482$ ,  $N_Z - N_X = 0.002-0.005$ . *Ashtonite*<sup>135</sup> is probably a variety; it has  $N_X = 1.481$ ,  $N_Y = 1.482$ ,  $N_Z = 1.486$ ,  $N_Z - N_X = 0.005$ . Colorless, yellowish, pinkish.

OCCUR. Mordenite is found in cavities in basalt, as at Morden, Nova Scotia; Hoodoo Mountains, Wyoming, etc.

DIAG. It differs from heulandite in optic orientation and lower refringence.

## GISMONDITE



ORTHORHOMBIC DIPYRAMIDAL<sup>136</sup>

$$a:b:c = 0.958:1:0.742$$

COMP. In gismondite CaAl may be replaced by KSi (or NaSi).

STRUC. Space group<sup>137</sup>  $Cmmm$  or  $Ccca$ ;  $a$  13.68,  $b$  14.28,  $c$  10.60 Å. U.C. 1.

PHYS. CHAR. Crystals pseudotetragonal bipyramids produced by twinning on 110 and 001. Distinct 101 cleavage.  $H. = 4.5$ .  $G. = 2.27$ .  $F. = 3$  with intumescence. Gelatinizes with HCl.

OPT. PROP. Basal sections show four segments with opposite parts alike and extinction inclined at  $5^\circ$ . The edge of the pyramid corresponds with the clin-axis  $a$ . The optic plane and acute bisectrix  $X$  are normal to 010;  $Z$  is nearly normal to 100. Optic angle large.  $(- )2V = 82^\circ-86^\circ$ ,  $N_X = 1.5308$ ,  $N_Y = 1.5402$ ,  $N_Z =$

<sup>132</sup> C. Waymouth, P. C. Thornely, and W. H. Taylor: *Mineral. Mag.*, XXV, 212 (1938). *Ptilolite* is shown to be a synonym of mordenite.

<sup>134</sup> E. V. Shannon: *U. S. Nat. Mus. Bull.* 131, 346 (1926); G. D'Achiardi: *Atti Soc. Toscana Sci. Nat.*, XXII, 150 (1906); L. H. Koch: *Am. Mineral.*, II, 143 (1917).

<sup>135</sup> E. Poitevin: *Am. Mineral.*, XVII, 120 (1932).

<sup>136</sup> G. Kalb: *Zeit. Krist.*, LXXXI, 248 (1932).

<sup>137</sup> O. Kraus: *Cent. Mineral.*, 1939A, 105.

1.5484 Na,  $N_Z - N_X = 0.0176$  (Hibsch<sup>138</sup>).  $2V = 82^\circ 43'$ ,  $N_Y = 1.5385$  Na (Rinne<sup>139</sup>);  $N_Z - N_X = 0.008$  (Lacroix<sup>140</sup>).  $N_X = 1.538$ ,  $N_Y = 1.543$ ,  $N_Z = 1.548$ ,  $N_Z - N_X = 0.010$  (Dunham<sup>141</sup>). Colorless, white, or grayish.

**OCCUR.** Gismondite is found in cavities in volcanic and other rocks, often with phillipsite, as at Salesl, Bohemia.

**DIAG.** The external form is characteristic; the twinning is notable.

**Armenite**<sup>142</sup> ( $\text{BaCa}_2\text{Si}_8\text{Al}_6\text{O}_{28} \cdot 2\text{H}_2\text{O}$ ?) is orthorhombic with pseudohexagonal twinning. Perfect 010 and good 110 cleavages.  $H. = 7.5$ .  $G. = 2.76$ .  $X = c$ ;  $Z = b$ .  $(-)2V = 60^\circ$ ,  $N_X = 1.551$  calc.,  $N_Y = 1.559$ ,  $N_Z = 1.562$ ,  $N_Z - N_X = 0.011$  calc. Found at the Armen mine, Kongsberg, Norway.

## NATROLITE      ORTHORHOMBIC PYRAMIDAL      $\text{Na}_2\text{Si}_3\text{Al}_2\text{O}_{10} \cdot 2\text{H}_2\text{O}$

$$a:b:c^{143} = 0.984:1:0.349$$

**STRUC.** Space group<sup>143</sup>  $Fdd$ ;  $a$  18.3,  $b$  18.6,  $c$  6.57 Å. U.C. 8.

**PHYS. CHAR.** Crystals nearly always prismatic, vertically striated, pseudotetragonal, acicular to fibrous parallel to  $c$ . Twinning rare. Perfect 110 cleavage and 010 parting. Shows pyroelectric property.  $H. = 5-5.5$ .  $G. = 2.25$ .  $F. = 2$ . Gelatinizes with HCl.

**OPT. PROP.** The optic plane is 010;  $Z = c$ . See Fig. 229. The negative relief is distinct, and the birefringence is greater than that of quartz.

$(+)2V = 60^\circ-63^\circ$ ,  $r < v$  weak.  $N_X = 1.473-1.480$ ,  $N_Y = 1.476-1.482$ ,  $N_Z = 1.485-1.493$ ,  $N_Z - N_X = 0.011-0.013$ .

Color white, colorless, grayish, yellowish; colorless in section.

**OCCUR.** Natrolite is found in cavities in basalt; also as an alteration product of nepheline, sodalite, plagioclase in syenite, diabase, etc.

**DIAG.** Natrolite is characterized by low refringence, parallel extinction, positive optic sign, and positive elongation.

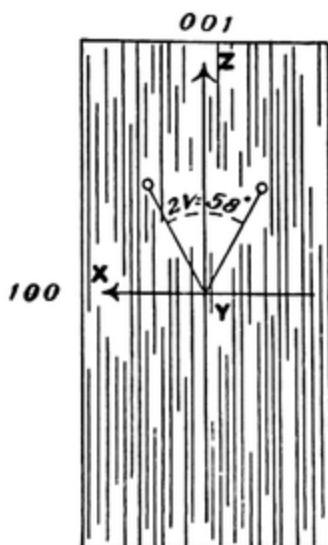


FIG. 229. The optic orientation of natrolite.

<sup>138</sup> J. E. Hibsch: *Tsch. Min. Pet. Mit.*, XXXIV, 187 (1917).

<sup>139</sup> F. Rinne: *Zeit. Krist.*, XX, 302 (1892).

<sup>140</sup> A. Lacroix: *Minéraux des Roches*, 306 (1888).

<sup>141</sup> K. C. Dunham: *Am. Mineral.*, XVIII, 369 (1933).

<sup>142</sup> H. Neumann: *Norsk. Geol. Tidssk.*, XIX, 312 (1939); XXI, 19 (1941); *Norg. Geol. Unders.*, 162 (1944). Armenite is chemically like a zeolite, but its water is stable to about  $450^\circ$ .

<sup>143</sup> W. H. Taylor, C. A. Meek, and W. W. Jackson: *Zeit. Krist.*, LXXXIV, 373 (1933); J. Wyart: *Bull. Soc. Fr. Min.*, LVI, 81 (1933). M. H. Hey: *Mineral. Mag.*, XXIV, 227 (1936).



## SCOLECITE

## MONOCLINIC DOMATIC



$$a:b:c = 0.975:1:0.345 \quad \beta = 90^\circ 42'$$

STRUC. Space group  $^{143} Cc$ ;  $a$  18.48,  $b$  18.95,  $c$  6.54 Å. U.C. 8.

PHYS. CHAR. Crystals slender prismatic, vertically striated; often in fibrous masses. Twinning on 100; rarely on 110 or 001. Nearly perfect 110 cleavages.  $H. = 5$ .  $G. = 2.3$ .  $F. = 2$ , curling into wormlike forms (whence the name). Gelatinizes with HCl.

OPT. PROP. The optic plane and  $Z$  are normal to 010;  $X \wedge c = 15^\circ - 18^\circ$  in the obtuse angle  $\beta$ . See Fig. 230.  $(- )2V = 36^\circ \text{ ca.}$   $r < v$  distinct.  $N_X = 1.5122$ ,  $N_Y = 1.5187$ ,  $N_Z = 1.5194$ ,  $N_Z - N_X = 0.0083$ . Colorless or white.

INVER. Scolecite inverts to *metascolecite*  $^{144}$  at about  $200^\circ$  to  $250^\circ$ ; at this temperature under ordinary vapor pressure there is a loss of about  $8\text{H}_2\text{O}$  (from  $24\text{H}_2\text{O}$  in U.C.). *Metascolecite* with  $16\text{H}_2\text{O}$  per unit cell has  $X$  normal to 010 ( $=100$  of scolecite) and  $Y \wedge c = 18^\circ$ ,  $(- )2V = 65^\circ$ ,  $r < v$ ,  $N = 1.505$ ,  $N_Z - N_X = 0.01$ ; with about  $5\text{H}_2\text{O}$  per unit cell it has  $Y \wedge c = 5^\circ$ ,  $(- )2V = 65^\circ$ ,  $r < v$ ,  $N = 1.523$ ,  $N_Z - N_X =$  very weak.

OCCUR. Scolecite is found in cavities in basalt and also in schists and contact zones. Found at Table Mountain, Colorado, etc.

DIAG. Scolecite differs from natrolite by its inclined extinction and negative elongation; from thomsonite by its weaker birefringence, inclined extinction, and negative elongation; from mesolite by its stronger birefringence, larger extinction angle, and negative elongation; and from stilbite by its larger extinction angle.

MESOLITE  $^{145}$ 

## MONOCLINIC SPHENOIDAL



$$a:b:c = 8.658:1:2.813 \quad \beta = 90^\circ 0' \pm 20'$$

COMP. Mesolite may contain a little K.

STRUC. Space group  $C2$ ;  $a$  56.7,  $b$  6.54,  $c$  18.44 Å. U.C. 8.

PHYS. CHAR. Crystals often fibrous elongated along  $b$ . Twinning constant on 100 (also 001), visible only microscopically. Perfect 301 and  $\bar{3}01$ -cleavages.  $H. = 5$ .  $G. = 2.27$ .  $F.$  = easy with swelling to vermicular forms. Gelatinizes with HCl.

OPT. PROP. The optic plane is 010 (normal to elongation);  $X \wedge c = 8^\circ$ .  $(+ )2V =$  about  $85^\circ$  at  $15^\circ \text{ C.}$ , with  $r < v$  strong, but the optic angle increases rapidly on heating, becoming  $90^\circ$  at  $20^\circ \text{ C.}$  with change of sign to negative above  $20^\circ \text{ C.}$  Then measured about  $X$  the optic angle decreases rapidly becoming  $0^\circ$  at  $59^\circ \text{ C.}$ ; above that temperature the optic plane is nearly parallel to 001.

$N_X = 1.5048$ ,  $N_Y = 1.5050$ ,  $N_Z = 1.5053$ ,  $N_Z - N_X = 0.0005$  (Görgey  $^{146}$ ).  $N_X = 1.5073$ ,  $N_Y = 1.5074$ ,  $N_Z = 1.5075$ ,  $N_Z - N_X = 0.0002$  (Hey  $^{145}$ ).  $F - C$  for  $N_Y = 0.0042$ .

$^{144}$  F. Rinne: *Sitzb. Preuss. Akad. Wiss.*, 1890, 1163; M. H. Hey: *Mineral. Mag.*, XXIV, 227 (1936).

$^{145}$  M. H. Hey: *Mineral. Mag.*, XXIII, 421 (1933).

$^{146}$  R. Görgey: *Tsch. Min. Pet. Mit.*, XXVIII, 77 (1909).

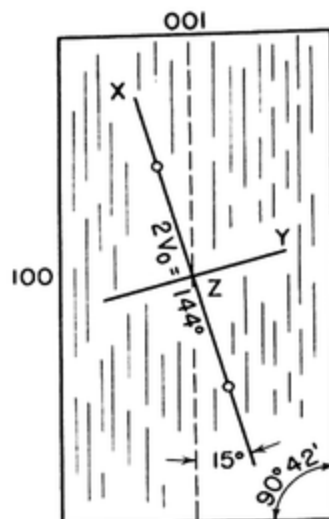


FIG. 230. The optic orientation of scolecite.

Colorless, white, gray, or yellowish. Colorless in thin section.

**OCCUR.** Mesolite is found in cavities in basic igneous rocks, as at Gates Mountain, Nova Scotia.

**DIAG.** Mesolite differs from other zeolites in its  $\pm$  sign of elongation and extremely weak birefringence.

**Pseudomesolite** is chemically like mesolite but optically different; its form is also like that of mesolite, but twinning is unknown in it; it has distinct prismatic cleavage and a large extinction angle with  $Z \wedge c = 20^\circ$ , and X and Y in such positions as to give extinction sensibly parallel with the diagonals of the rhombs formed by the prism faces in cross sections. The optic angle is small about Z; the birefringence is very weak, and the relief is negative. Color in mass porcelain white or stained pinkish or grayish. Pseudomesolite is found in cavities in basic igneous rocks in northern Minnesota.

### LAUMONTITE

MONOCLINIC



$$a:b:c = 1.145:1:0.591 \quad \beta = 111^\circ 14'$$

**COMP.** In laumontite NaSi can replace CaAl as indicated,  $\text{Fe}'''$  can replace  $^{147}\text{Al}$  in small part; K may be present;  $\text{H}_2\text{O}$  is variable.

**PHYS. CHAR.** Crystals prismatic somewhat like pyroxene. Twinning on 100. Perfect 010 and 110 cleavages.  $H. = 3-4$ .  $G. = 2.23-2.41$ .  $F. = 2.5$  with swelling. Gelatinizes with HCl.

**OPT. PROP.** The optic plane is 010;  $Z \wedge c = 20^\circ-40^\circ$  in the acute angle  $\beta$ . See Fig. 231. Optic angle moderate to small with  $r < v$  distinct and weak inclined dispersion.

	Larsen <sup>41</sup>	Glass <sup>147</sup>	Dunham <sup>148</sup>	Woodford <sup>149</sup>	Shannon <sup>150</sup>	Whitehouse <sup>151</sup>
(-)2V =	25° ca.	25°-35°	Small		Med.	
N <sub>X</sub> =	1.513	1.504	1.511		1.505	1.508
N <sub>Y</sub> =	1.524	1.514	1.518		1.515	
N <sub>Z</sub> =	1.525	1.516	1.522	1.515-1.526	1.517	1.524
N <sub>Z</sub> - N <sub>X</sub> =	0.012	0.012	0.011		0.012	0.016
Z $\wedge$ c =	20°-30°	30°-36°			Large	

Color white, glassy, yellowish, grayish. Colorless in thin section.

**ALTER.** Laumontite easily loses about one-eighth of its water, often simultaneously falling to a powder, and is then called *caporcianite* (with  $^{149}\text{N}_Z = 1.515-1.517$  and  $^{152}\text{Z} \wedge c = 40^\circ$ ). By base exchange laumontite may lose about one-third of its Ca, acquiring  $\text{K}_2$  (and  $\text{Na}_2$ ); at the same time it loses some water; it is then called *leonhardite* and has indices that are lowered 0.003 or more; a sample <sup>153</sup> from Devon

<sup>147</sup> E. P. Henderson and J. J. Glass: *Am. Mineral.*, XVIII, 402 (1933).

<sup>148</sup> K. C. Dunham: *Am. Mineral.*, XVIII, 369 (1933).

<sup>149</sup> A. O. Woodford, R. A. Crippen, and K. B. Garner: *Am. Mineral.*, XXVI, 371 (1941).

<sup>150</sup> E. V. Shannon: *Am. Mineral.*, VI, 6 (1921).

<sup>151</sup> Marjorie J. Whitehouse: *Mineral. Mag.*, XXIV, 538 (1937).

<sup>152</sup> T. L. Walker: *Univ. Toronto Geol. Stud.*, 14, 57 (1922).

<sup>153</sup> C. O. Hutton: *Trans. Roy. Soc. N. Zeal.*, LXXIV, 125 (1944).

Well has  $(-)2V = 35^\circ-38^\circ$ ,  $N_X = 1.502$ ,  $N_Y = 1.512$ ,  $N_Z = 1.514$ ,  $N_Z - N_X = 0.012$ .

**OCCUR.** Laumontite is found in veins in schists, slates, etc.; also in cavities in igneous rocks, as at Peter's Point, Nova Scotia, and Bergen Hill, New Jersey.

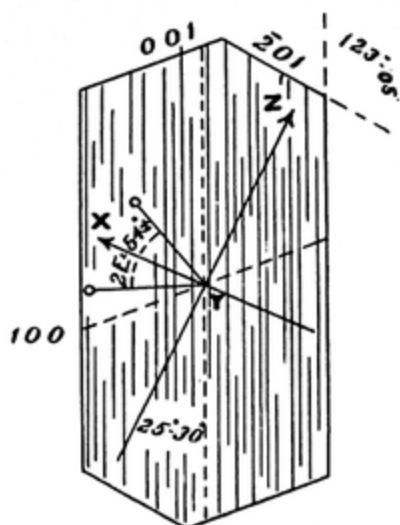


FIG. 231. The optic orientation of laumontite.

**DIAG.** The perfect cleavages in three directions in one zone are quite distinctive. Further, the mineral has positive elongation with a large extinction angle, and stronger birefringence than phillipsite.

**PHILLIPSITE** (*Christianite*)      **MONOCLINIC**       $\left\{ mKCa_3Si_9Al_7O_{32} \cdot 12H_2O + \right\} (?)$   
 $nK_3CaSi_{11}Al_5O_{32} \cdot 12H_2O$   
 $a:b:c^{154} = 0.702:1:0.605$        $\beta = 125^\circ$

**COMP.** In phillipsite CaAl may be replaced by KSi as indicated. Ba may be present.

**STRUC.** Space group  $^{154} P2_1/m$  or  $P2_1$ ;  $a$  10.00,  $b$  14.25,  $c$  8.62 Å. U.C. 1.

**PHYS. CHAR.** Crystals penetration twins apparently orthorhombic or tetragonal. Twinning on 100; also often on 120 as rectangular crosses in two or three directions. Also in spherulites. Elongation along  $c$ . Distinct 001 and 010 cleavages.  $H. = 4-4.5$ .  $G. = 2.2$ .  $F. = 3$ , to white enamel. Gelatinizes with HCl.

**OPT. PROP.** The optic plane and  $X$  are normal to 010;  $Z \wedge c = 11^\circ$  to  $30^\circ$  in the acute angle  $\beta$ . See Fig. 232. Sometimes it is apparently triclinic since sections parallel to 100 show extinction at  $10^\circ+$  to  $c$ . Optic angle large, variable. Apparently the most siliceous phillipsite crystals have the lowest index (about 1.48) with  $Z \wedge c = 10^\circ$  ca., and  $N_Z - N_X = 0.003$ , while the least siliceous crystals have  $N =$  about 1.51, with  $Z \wedge c = 30^\circ$  ca., and  $N_Z - N_X = 0.010$ . The optic angle varies from  $(+)2V = 60^\circ$  to  $80^\circ$  and perhaps more.<sup>155</sup> Dispersion  $r < v$  weak. A sample from Honolulu has  $^{141} (-)2V =$  moderate,  $N_X = 1.493$ ,  $N_Y = 1.497$ ,  $N_Z = 1.500$ ,  $N_Z - N_X = 0.007$ . Colorless, white, or stained yellow or reddish.

<sup>154</sup> J. Wyart and P. Chatelain: *Bull. Soc. Fr. Min.*, LXI, 121 (1938).

<sup>155</sup> S. Richarz (*Zeit. Dtsch. Geol. Ges.*, LXXII, 1, 1920) reports phillipsite with  $(-)2V = 60^\circ-65^\circ$  and  $Z \wedge c = 24^\circ-25^\circ$ .

**OCCUR.** Phillipsite is found in druses in igneous rocks; common in red clay and deep-sea deposits; also formed from some hot spring waters; often associated with chabazite, less frequently with thomsonite, calcite, apophyllite.

**DIAG.** The twinning of phillipsite is quite characteristic except as compared with harmotome, which is rare and has different optic orientation.

**Wellsite** is chemically a barium-bearing phillipsite, but it is otherwise quite distinct, having  $a:b:c = 0.768:1:1.245$ ,  $\beta = 126^\circ 33'$ . Complex twins. No cleavage.  $H. = 4-4.5$ .  $G. = 2.28-2.37$ . The optic plane and  $Z$  are normal to  $010$ ;  $X \wedge c^{100} = -52^\circ$ .  $(+)2V = 39^\circ$ ,  $N_X = 1.498$ ,  $N_Y = 1.50$ ,  $N_Z = 1.503$ ,  $N_Z - N_X = 0.005$  (Larsen<sup>41</sup>). Colorless. Found in Clay County, North Carolina, and at Kurzy in the Crimea.

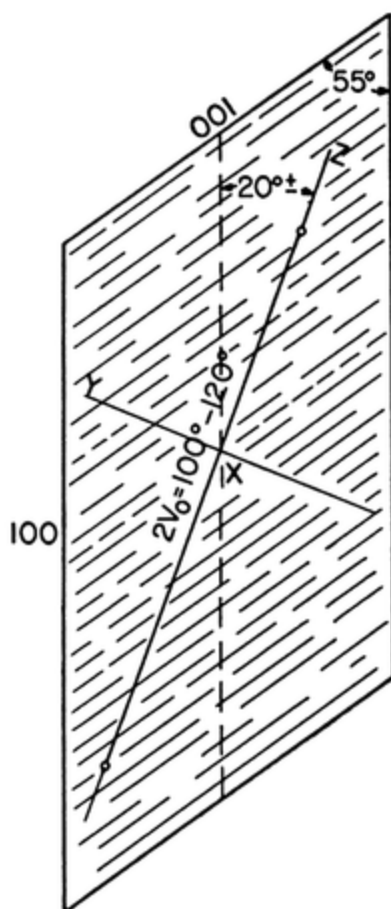


FIG. 232. The optic orientation of phillipsite.

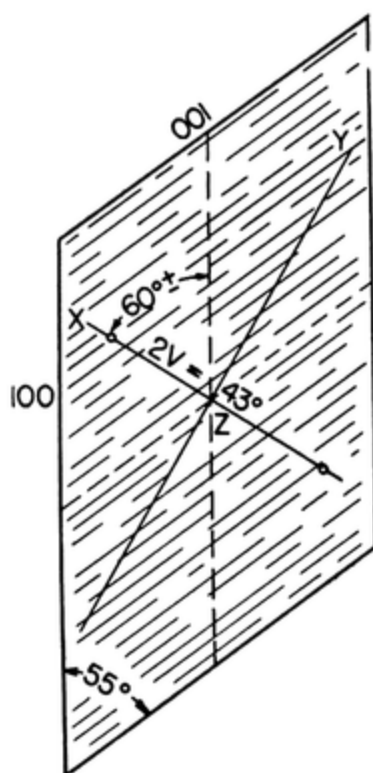


FIG. 233. The optic orientation of harmotome.

## HARMOTOME

MONOCLINIC PRISMATIC



$$a:b:c = 0.695:1:0.614 \quad \beta = 124^\circ 50'$$

**COMP.** Harmotome may contain some K, Na, and Ca.

**STRUC.** Space group <sup>157</sup>  $P2_1/m$ ;  $a$  9.80,  $b$  14.10,  $c$  8.66 Å. U.C. 1.

**PHYS. CHAR.** Crystals similar to those of phillipsite, elongated along  $c$ . Distinct 010 and poor 001 cleavages. Cruciform twins.  $H. = 4.5$ .  $G. = 2.44-2.50$ .  $F. = 3.5$  without intumescence to white glass. Decomposed by HCl.

<sup>156</sup> J. H. Pratt and H. W. Foote: *Am. Jour. Sci.*, III, 443 (1897).

<sup>157</sup> A. E. Meier: *Am. Mineral.*, XXIV, 540 (1939). J. Sekanina and J. Wyart: *Bull. Soc. Fr. Min.*, LX, 139 (1937).

**Opt. Prop.** The optic plane and  $Z$  are normal to 010;  $X \wedge c = -58^\circ$ . See Fig. 233. Weak crossed dispersion.  $(+ )2V = 79^\circ$ ,  $N_X = 1.503$ ,  $N_Y = 1.505$ ,  $N_Z = 1.508$ ,  $N_Z - N_X = 0.005$ . On heating the extinction angle increases (to  $82^\circ$  at  $130^\circ \text{C.}$ ). But the optic angle decreases rapidly on heating, becoming  $32^\circ$  at  $130^\circ \text{C.}$  Heat due to grinding a thin section may produce <sup>157</sup> an optic angle of  $32^\circ$ . Colorless.

**Occur.** Harmotome is found in cavities in basalt and other rocks, as at Strontian, Scotland; Kongsberg, Norway; Rabbit Mountain, Ontario, etc.

**Diag.** It is distinguished from phillipsite by greater specific gravity and different optic orientation.

**STILBITE** MONOCLINIC PRISMATIC  $\left\{ \begin{array}{l} m\text{Ca}_6\text{Si}_{24}\text{Al}_{12}\text{O}_{72} \cdot 28\text{H}_2\text{O} + \\ n\text{Na}_2\text{Ca}_4\text{Si}_{26}\text{Al}_{10}\text{O}_{72} \cdot 28\text{H}_2\text{O} \end{array} \right.$   
 $a:b:c$  <sup>158</sup> = 0.750:1:0.623  $\beta = 128^\circ \text{ca.}$

**Comp.** Stilbite varies only a little in composition; without Na it has been called *stellerite*.<sup>159</sup>

**Struc.** Space group  $C2/m$ ;  $a$  13.60,  $b$  18.13,  $c$  11.29 Å. U.C. 1.

**Phys. Char.** Crystals always twinned as crosses on 100 to pseudorhombic forms. Usually flattened parallel to 010 and always elongated along  $c$ . Often in sheaflike aggregates. Perfect 010 and poor 100 cleavages.<sup>159a</sup>  $H. = 3.5-4$ .  $G. = 2.09-2.20$ .  $F. = 3$ , with exfoliation to white enamel. Decomposed by HCl.

**Opt. Prop.** The optic plane is parallel to 010;  $X \wedge a = +5^\circ$  ( $3^\circ$  to  $12^\circ$ ); the optic angle is not large. See Fig. 234.

	Culpeper, Va. <sup>160</sup>	Adamello, Italy <sup>161</sup>	Chelan Co., Wash. <sup>162</sup>	Goose Creek, Va. <sup>163</sup>	Copper Isl., Bering Sea <sup>164</sup>	Norway <sup>165</sup>
$(- )2V = 30^\circ \text{ca.}$		$32.5^\circ$	$48^\circ$		$43.5^\circ$	$49^\circ$
$N_X = 1.489$		1.492	1.487	1.490	1.484	1.482
$N_Y = 1.498$		1.499	1.498	1.500	1.49	1.491 calc.
$N_Z = 1.499$		1.501	1.500	1.502	1.495	1.493
$N_Z - N_X = 0.010$		0.009	0.013	0.012	0.011	0.011
$X \wedge a = \text{Small}$			$7^\circ$	$0^\circ \text{ca.}$	$0^\circ \text{ca.}$	

Color white or yellowish. Colorless in section.

**Occur.** Stilbite is found in cavities in basalt and other rocks; also in some hot spring deposits. Found at Chester, Massachusetts; Bergen Hill, New Jersey, etc.

<sup>158</sup> J. Sekanina and J. Wyart: *Bull. Soc. Fr. Min.*, LIX, 377 (1936).

<sup>159</sup> H. Neumann: *Norges Geol. Unders.*, 162 (1944).

<sup>159a</sup> Pseudo-orthorhombic orientation of Tschermak. (*Sitz. Akad. Wien*, CXXVI, p. 600); relation to structural orientation is not clear.

<sup>160</sup> R. O. Bloomer: *Am. Mineral.*, XXII, 309 (1937).

<sup>161</sup> M. Fenoglio: *Min. Abst.*, VIII, 318 (1943).

<sup>162</sup> W. M. Chappell: *Am. Mineral.*, XVIII, 440 (1933).

<sup>163</sup> E. V. Shannon: *Proc. U. S. Nat. Mus.*, LXVI, Art. 2, 72 (1924).

<sup>164</sup> J. Morozewicz: *Bull. Int. Acad. Sci. Cracovie*, 1909, 344. A. Pabst (*Mineral. Mag.*, XXV, 271, 1938) has shown that *stellerite* and *epidesmine* are stilbite.

<sup>165</sup> H. Neumann: *Norges Geol. Unders.*, 162 (1944).

DIAG. It differs from phillipsite and harmotome in its lamellar aggregate condition and its cleavage, as well as by its sign of elongation

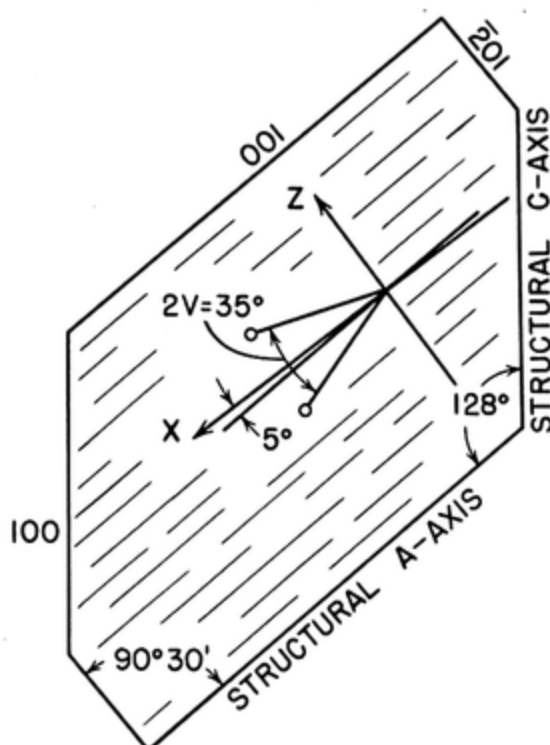


FIG. 234. The optic orientation of stilbite.<sup>159a</sup>

and extinction angles. It differs from heulandite in optic sign and optic orientation.

### EPISTILBITE

MONOCLINIC



$$a:b:c = 0.419:1:0.432 \quad \beta = 90^\circ 40'$$

COMP. No modern analyses known.

PHYS. CHAR. Crystals always prismatic, twinned; radiated spherical aggregates. Twinning on 100 or 010 may form penetration crosses. Perfect 010 cleavage.  $H. = 4$ .  $G. = 2.25$ .  $F. = 5$  with intumescence. Decomposed by HCl.

OPT. PROP. The optic plane is 010 and  $Z \wedge c = 10^\circ$  in the acute angle  $\beta$ . See Fig. 235. The vertical elongation is positive.  $(+)2E = 69^\circ-73^\circ \text{ Li}, 72^\circ-77^\circ \text{ Tl}$ ;  $2V = 44^\circ$ ,  $N_X = 1.502$ ,  $N_Y = 1.510$ ,  $N_Z = 1.512$ ,  $N_Z - N_X = 0.010$  (Larsen<sup>41</sup>);  $N_X = 1.505$ ,  $N_Y = 1.515$ ,  $N_Z = 1.519$ ,  $N_Z - N_X = 0.014$  (Dunham<sup>141</sup>).

Colorless, white, or pinkish. Colorless in thin section.

OCCUR. Epistilbite is often associated with stilbite in cavities in rocks, as at Poona, India, and Bergen Hill, New Jersey.

DIAG. It differs from stilbite and mesolite in the sign of elongation, and has a smaller extinction angle than phillipsite.

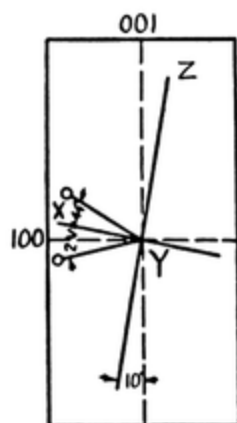


FIG. 235. The optic orientation of epistilbite.



**BREWSTERITE**MONOCLINIC  $Na(Sr,Ba,Ca)_5Si_{29}Al_{11}O_{80} \cdot 25H_2O$ 

$$a:b:c = 0.405:1:0.420 \quad \beta = 93^\circ 40'$$

**PHYS. CHAR.** Crystals commonly prismatic, somewhat vertically elongated and striated, and flattened parallel to 010. Perfect 010 cleavage.  $H. = 5$ .  $G. = 2.45$ .  $F. = 3$ , with swelling. Decomposed by HCl.

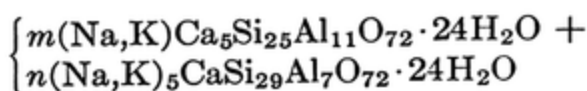
**OPT. PROP.** The optic plane and  $Z$  are normal to 010;  $X \wedge c = 22^\circ$  *ca.* in the obtuse angle  $\beta$ ; the extinction angle varies from  $19^\circ$  to  $34^\circ$  in various parts of zonal crystals.  $(+ )2V = 65^\circ \pm$ ,  $r > v$  weak; also weak crossed dispersion.  $N_X = 1.510$ ,  $N_Y = 1.512$ ,  $N_Z = 1.523$ ,  $N_Z - N_X = 0.013$  (Larsen<sup>168</sup>).

Color white, yellowish, or greenish. Colorless in thin section.

**ALTER.** HCl alters brewsterite to hydrous silica,<sup>167</sup> but with properties like the original.

**OCCUR.** Brewsterite is found in drusy cavities in schists and basalts, as at Strontian, Scotland; Barèges, France, etc.

**DIAG.** It differs from heulandite and epistilbite in optic orientation.

**HEULANDITE**

MONOCLINIC PRISMATIC

$$a:b:c = 0.418:1:0.891 \quad \beta = 91^\circ 26'$$

**COMP.**<sup>168</sup> Besides the variation shown,  $Na_2$  may replace  $Ca$  to some extent (secondary?).  $H_2O$  often deficient (due to loss in dry air?).

**STRUC.** Space group<sup>169</sup>  $C2/m$ ;  $a$  7.45,  $b$  17.80,  $c$  15.85 Å. U.C. 1.

**PHYS. CHAR.** Crystals often {010} tablets or nearly equant, of orthorhombic aspect. Aggregates of nearly parallel units. Perfect 010 cleavage.  $H. = 3.5-4$ .  $G. = 2.2$ .  $F. = 2$ , after swelling to vermicular forms.

**OPT. PROP.** The optic plane and  $Z$  are normal to 010;  $X \wedge c = 68^\circ-82^\circ$  (also reported as  $35^\circ$  *ca.*<sup>170</sup> and  $\pm 2^\circ$ <sup>171</sup>).  $(+ )2E = 0^\circ-92^\circ$ , usually near  $50^\circ$ ,  $2V = 34^\circ$  *ca.*,  $r > v$ , with distinct crossed dispersion.  $N_X = 1.498$ ,  $N_Y = 1.499$ ,  $N_Z = 1.505$ ,  $N_Z - N_X = 0.007$ . Again:  $N_X = 1.496$ ,  $N_Y = 1.497$ ,  $N_Z = 1.501$ ,  $N_Z - N_X = 0.006$  (Parsons<sup>172</sup>). Heulandite rich in silica<sup>173</sup> ( $SiO_2 = 61.83$ ) has  $N_X$  and  $N_Y = 1.487-1.488$ ,  $N_Z = 1.488-1.489$ ,  $N_Z - N_X = 0.001$ . Optical properties vary markedly during loss of water on heating.<sup>174</sup>

<sup>168</sup> Personal communication, Sept. 18, 1925.

<sup>167</sup> F. Rinne: *Fortsch. Min.*, III, 159 (1913).

<sup>168</sup> M. H. Hey and F. A. Bannister: *Mineral. Mag.*, XXIII, 556 (1934).

<sup>169</sup> J. Wyart: *Bull. Soc. Fr. Min.*, LVI, 81 (1933). *Min. Abst.*, IV, 369 (1931).

<sup>170</sup> E. V. Shannon: *Bull. U. S. Nat. Mus.*, 131, 346 (1926).

<sup>171</sup> G. Resegotti: *Min. Abst.*, V, 83 (1932).

<sup>172</sup> A. L. Parsons: *Univ. Toronto Geol. Stud.*, 14, 52 (1922).

<sup>173</sup> H. Heritsch: *Zent. Mineral.*, 1940A, 227.

<sup>174</sup> F. Rinne: *Ber. Akad. Berlin*, 1890, 1183.

Colorless, white, or stained yellowish, gray, brown, or red. Colorless in thin section.

**ALTER.** HCl alters heulandite to hydrous silica,<sup>175</sup> but with properties like the original.

**OCCUR.** Heulandite is found especially in cavities in basalts; also in schists; usually with other zeolites. Found at Bernfiord, Iceland; Bombay, India; near Pigeon Bay, Ontario.

**DIAG.** It is rarely fibrous, but has a lamellar cleavage with the positive acute bisectrix normal thereto. Epistilbite, mordenite, and brewsterite are similar, but differ in optic orientation.

**Dachiardite** <sup>176</sup> ( $\text{Na}_2\text{K}_2\text{Ca}_2\text{Si}_{32}\text{Al}_8\text{O}_{80}\cdot 25\text{H}_2\text{O}$ ?) is monoclinic with  $a:b:c = 2.48:1:1.37$ ,  $\beta = 107^\circ 49'$ . Crystals prismatic with constant twinning on 110, often cyclic pseudotetragonal. Perfect 100 and 001 cleavages.  $H. = 4-4.5$ .  $G. = 2.165$ . Decomposed by HCl. The optic plane and  $X$  are normal to 010;  $Z \wedge c = 35^\circ$ .  $(+ )2V = 65^\circ$ ,  $N_X = 1.492$ ,  $N_Y = 1.496$ ,  $N_Z = 1.500$ ,  $N_Z - N_X = 0.008$ . Colorless. Found with other zeolites on the island of Elba.

**Laubanite** ( $\text{Ca}_2\text{Si}_5\text{Al}_2\text{O}_{15}\cdot 6\text{H}_2\text{O}$ ?) is fibrous and perhaps monoclinic, although apparently uniaxial. Good prismatic cleavage.  $H. = 4.5$ .  $G. = 2.2$ . Fuses to a blebby glass. Gelatinizes with HCl.  $(+ )2V = 0^\circ$ ,  $N_X = N_Y = 1.475$ ,  $N_Z = 1.486$ ,  $N_Z - N_X = 0.011$ . Color white. Found with phillipsite in basalt at Lauban, Silesia.

## (b) WITH ADDITIONAL ANIONS

### SODALITE GROUP

The sodalite group includes four minerals which are silicates of aluminum and sodium with also some chlorine or sulfur. They are closely related, and continuous series seem quite possible but are not yet proved. All are isometric; the chemical formulas are still somewhat doubtful, but probably as follows:

Sodalite	$6\text{NaSiAlO}_4\cdot 2\text{NaCl}$ or $\text{Na}_4\text{Al}_3\text{ClSi}_3\text{O}_{12}$
Noselite	$6\text{NaSiAlO}_4\cdot \text{Na}_2\text{SO}_4$ or $\text{Na}_8\text{Al}_6\text{SO}_4\text{Si}_6\text{O}_{24}$
Haüynite	$6\text{NaSiAlO}_4\cdot 2\text{CaSO}_4$ or $\text{Na}_3\text{CaAl}_3\text{SO}_4\text{Si}_3\text{O}_{12}$
Lazurite	$6\text{NaSiAlO}_4\cdot \text{Na}_2\text{S}_4$ or $\text{Na}_4\text{Al}_3\text{S}_2\text{Si}_3\text{O}_{12}$

### SODALITE

### ISOMETRIC HEXTETRAHEDRAL



**COMP.** A little K may be present. *Hackmanite* is a variety containing some S (in place of Cl). It has  $N = 1.487$ . Color reddish violet, fading on exposure to light; fluorescent.

<sup>175</sup> F. Rinne: *Fortsch. Min.*, III, 159 (1913).

<sup>176</sup> H. Berman: *Am. Mineral.*, X, 421 (1925). See also S. Bonatti: *Min. Abst.*, X, 293 (1948).

STRUC. Space group <sup>177</sup>  $P\bar{4}3n$ ;  $a$  8.87 Å. U.C. 2;  $P\bar{4}3m$ ; <sup>178</sup>  $I\bar{4}3m$ .<sup>179</sup>

PHYS. CHAR. Crystals dodecahedral; often granular. Poor 110 cleavage. Twinning on 111.  $H. = 5.5-6$ .  $G. = 2.35$ .  $F. = 3.5-4$  to colorless glass. Powdered material yields NaCl in boiling water. Gelatinizes even in acetic acid.

OPT. PROP. Isotropic with  $N = 1.483$  (to 1.487); a Bolivian sample gave: <sup>180</sup>  $N = 1.4806$  Li, 1.4837 Na, 1.4868 Tl; rarely birefringent about inclusions. Colorless, gray, yellow, blue, greenish, pale red. In thin section colorless, yellow, blue, pink; not pleochroic. Some samples are pink when freshly broken, fading quickly on exposure to light.<sup>181</sup> Some sodalite fluoresces <sup>182</sup> in ultraviolet light.

ALTER. Sodalite alters easily to a fibrous mass of zeolites, especially natrolite, or to a lamellar aggregate of sericite, gibbsite, diaspore, etc., or to cancrinite or garnet, etc.; calcite and limonite may form at the same time.

OCCUR. Sodalite is found in igneous rocks rich in soda, or, rarely, in limestone modified by such rocks. It is often associated with nepheline, from which it may form by alteration.

DIAG. The minerals of the sodalite group are distinguished by their very low refractive index from most other isotropic substances, the chief exceptions being volcanic glass, fluorite, leucite, and analcite. They are distinguished from these by their form, cleavage, absence of complex twinning, and chemical reactions. The minerals of the sodalite group may be distinguished from one another by the following test: cover the mineral on a glass slide with a little nitric acid which is allowed to evaporate slowly; in a short time crystals of NaCl may form, indicating sodalite, or crystals of  $CaSO_4 \cdot 2H_2O$ , indicating haüynite, or of neither before, and both after, addition of  $CaCl_2$ , indicating noselite; if  $H_2S$  (which blackens silver) is evolved during the attack by nitric acid, it indicates lazurite, which is further distinguished by its mode of occurrence as a contact mineral in limestone. Also, sodalite is usually colorless in thin section; the others are usually colored even in thin section, lazurite always being blue.

<sup>177</sup> L. Pauling: *Zeit. Krist.*, LXXIV, 213 (1930).

<sup>178</sup> T. F. W. Barth: *Zeit. Krist.*, LXXXIII, 405 (1932).

<sup>179</sup> M. Kolaczowska: *Min. Abst.*, VI, 178 (1935).

<sup>180</sup> W. Brendler: *Am. Mineral.*, XIX, 28 (1934).

<sup>181</sup> T. L. Walker and A. L. Parsons: *Am. Mineral.*, X, 66 (1925)

<sup>182</sup> A. Quinn: *Am. Mineral.*, XX, 466 (1935).

**NOSELITE** (*Nosean*)

ISOMETRIC HEXTETRAHEDRAL



COMP. Often contains some Ca, some Cl, some K, some  $\text{H}_2\text{O}$ .

STRUC. Space group  $^{183}P\bar{4}3n$ ;  $a$  9.05 Å. U.C. 1.

PHYS. CHAR. Crystals dodecahedral; often granular. Twinning on 111.  $H. = 5.5$ .  $G. = 2.3\text{--}2.4$ .  $F. = 5$  to a white glass. Gelatinizes easily with acids.

OPT. PROP. Nearly always isotropic with  $N = 1.48\text{--}1.495$ ; rarely birefringent if inclusions are present (due to strain?). Colorless, white, gray, lavender-blue, or yellowish brown, red, or black from inclusions or alteration products. In thin section a blue color may be very bright; it is usually irregularly distributed.

INCL. Microscopic inclusions, often abundant, are sometimes irregularly arranged in zones or along certain axes. They may be gaseous, liquid, vitreous, or crystalline; the last type may be magnetite or ilmenite of definite orientation and very abundant.

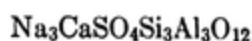
ALTER. Alters easily to a mass of sericite, gibbsite, zeolites, etc. Ferriferous inclusions may alter to limonite, giving a yellow or brown color.

OCCUR. Noselite is found exclusively in phonolites and similar igneous rocks, as in the Canary Islands.

DIAG. See sodalite.

**HAÜYNITE** (*Haüyne*)

ISOMETRIC HEXTETRAHEDRAL



COMP. Often contains some K, some Cl, some  $\text{H}_2\text{O}$ . Ca may be replaced (in part) by Na, thus grading toward noselite.

STRUC. Space group  $^{183}P\bar{4}3n$ ;  $a$  9.10 Å. U.C. 2.

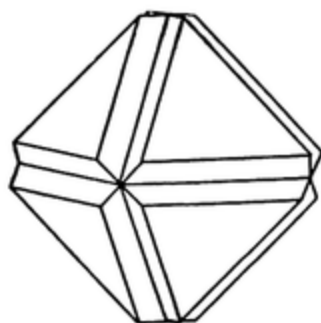


FIG. 236. A penetration twin of haüynite.

PHYS. CHAR. Crystals dodecahedral; often granular; twinning on 111, sometimes penetration twins as in Fig. 236.  $H. = 5.5\text{--}6$ .  $G. = 2.4\text{--}2.5$ .  $F. = 4.5$  to a white glass. Gelatinizes easily with acids.

OPT. PROP. Nearly always isotropic with  $N = 1.496\text{--}1.51$ ; rarely birefringent if inclusions are present (due to strain?). The index of refraction varies with the tenor of calcium as the mineral grades toward noselite. Color usually blue; also green, or, by alteration, yellow or red. Inclusions may produce a gray to black color. In thin section the blue color may be very bright; it is often irregularly distributed.

INCL. and ALTER. Similar to sodalite.

OCCUR. Haüynite is found exclusively in phonolites and related igneous rocks, usually associated with nepheline or leucite; found at Vesuvius; in the Crazy Mountains, Montana, etc.

DIAG. See sodalite.

**LAZURITE**

ISOMETRIC HEXTETRAHEDRAL



COMP. Lazurite varies much; S can be replaced at least in part by Se or Cl or  $\text{SO}_4$ ; in artificial lazurite  $^{184}$  (*ultramarine*) Na can be replaced by K, Rb, Cs, Ag, Mg, Ca, Sr, Ba, Zn, Mn,  $\text{NH}_4$ , methyl, ethyl, butyl.

STRUC. Space group  $P\bar{4}3n$ ;  $a$  9.11 (with Li,  $a$  8.67; with K,  $a$  9.4) Å. U.C. 2.

PHYS. CHAR. Crystals dodecahedral; often granular.  $H. = 5\text{--}5.5$ .  $G. = 2.38\text{--}2.45$ .  $F. = 5$  to a white glass. Gelatinizes easily with acid and yields  $\text{H}_2\text{S}$ .

$^{183}$  F. Machatschki: *Cent. Min.*, 1934A, 136.

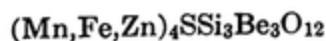
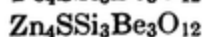
$^{184}$  F. M. Jaeger and F. A. van Melle: *Proc. Acad. Amsterdam*, XXX, 249, 479, 885 (1927), XXXII, 156, 167 (1929); *Bull. Soc. Fr. Min.*, LIII, 183 (1930).

**OPT. PROP.** Isotropic (or nearly so) with  $N = 1.50$  ca. Color blue both in mass and in thin section.

An orthorhombic(?) phase<sup>185</sup> of lazurite has been found in Siberia. It has  $(+)2V = 60^\circ$ ,  $N_X = 1.504$ ,  $N_Y = 1.510$ ,  $N_Z = 1.514$ ,  $N_Z - N_X = 0.010$ .

**OCCUR.** Lazurite is found exclusively in contact-altered limestone.

**DIAG.** See sodalite.

**HELVITE**ISOMETRIC HEXTETRAHEDRAL<sup>186</sup>**Helvite proper****Danalite****Genthelvite**

**COMP.** Helvite has three end-members,<sup>187</sup> shown above. A fourth (Mg) end-member seems possible.

**STRUC.** Space group<sup>186</sup>  $P\bar{4}3n$ ;  $a$  8.27 Å (Mn), 8.18 (Fe), 8.10 (Zn). U.C. 2.

**PHYS. CHAR.** Crystals tetrahedral with poor 111 cleavage.  $H. = 6$ .  $G. = 3.20$

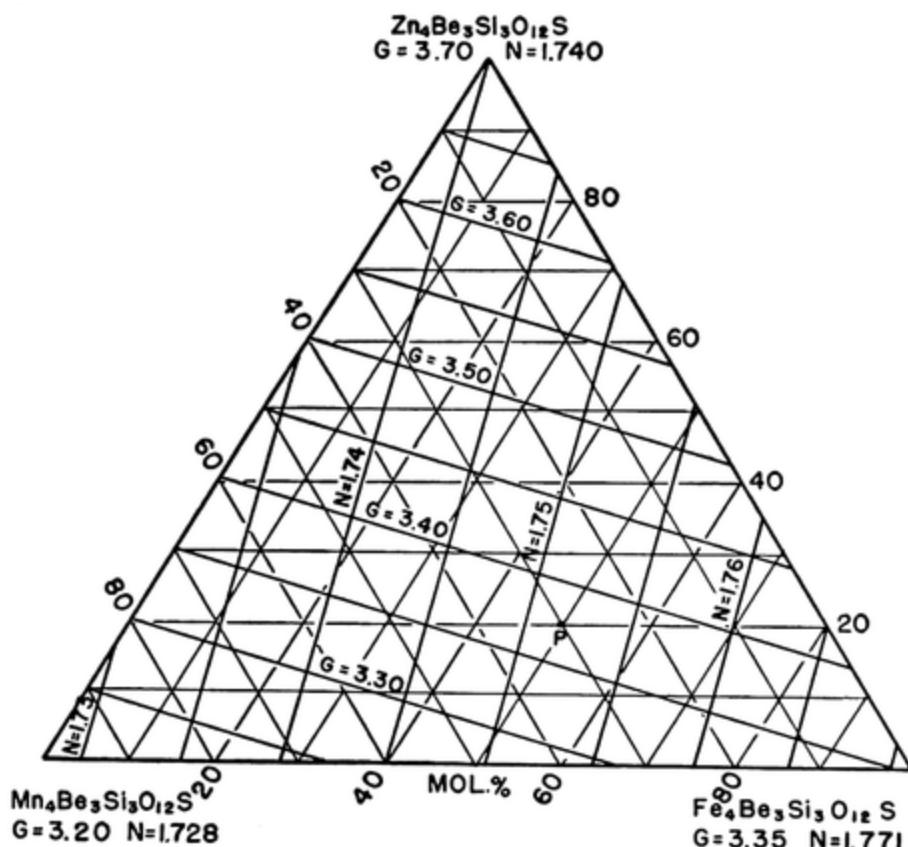


FIG. 237. Properties of helvite. After J. J. Glass, R. H. Jahns, and R. E. Stevens: *Am. Mineral.*, XXIX, 163 (1944).

(Mn), 3.35 (Fe), 3.70 (Zn). See Fig. 237.  $F. = 3$ . Gelatinizes with HCl with evolution of  $H_2S$ .

<sup>185</sup> N. V. Voskoboinikova: *Min. Abst.*, VII, 524 (1940).

<sup>186</sup> T. F. W. Barth: *Norsk. geol. Tidssk.*, IX, 40 (1926).

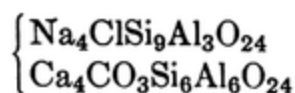
<sup>187</sup> J. J. Glass, R. H. Jahns, and R. E. Stevens: *Am. Mineral.*, XXIX, 163 (1944). H. Bowley (*Am. Mineral.*, XXX, 204, 1945) gives  $N = 1.747$  for helvite proper.

OPT. PROP. Isotropic with  $n_D^{187} = 1.728$  (Mn), 1.771 (Fe), 1.740 (Zn). See Fig. 237. Color yellow, red, brown, green, gray; in thin section paler.

OCCUR. Helvite is found rarely in gneiss, pegmatite, granite, or contact zones. Found at Kapnik, Hungary; Lupikko, Finland; Cape Ann, Massachusetts; etc.

DIAG. Helvite is characterized by high relief, isotropic character, and common triangular sections. A simple chemical test<sup>188</sup> is useful. Put the powdered sample in a small beaker and cover it with dilute HCl. Add a pinch of  $As_2O_3$  and boil about 1 minute. Decant the acid and wash the sample with water. Examine with binocular microscope. Any helvite present will be stained a brilliant canary yellow due to formation of  $As_2S_3$ .

### SCAPOLITE (*Wernerite*)



#### TETRAGONAL DIPYRAMIDAL

$$c/a = 0.44$$

COMP. Most crystals of scapolite belong at least approximately to the marialite ( $Na_4ClSi_9Al_3O_{24}$  or  $3NaAlSi_3O_8 \cdot NaCl = Ma$ )–meionite ( $Ca_4CO_3Si_6Al_6O_{24}$  or  $3CaAl_2Si_2O_8 \cdot CaCO_3 = Me$ ) series, but NaCl may be replaced at least in part by NaF, KCl, (KOH?),  $NaHCO_3$  or  $NaHSO_4$ , while  $CaCO_3$  may be replaced in part by  $CaSO_4$ ,  $MgCO_3$ , or  $CaCl_{(27)}$ , or perhaps by  $CaF_2$ . The chief scapolite series may be divided as follows:

Marialite	$c = 0.446$ (for pure Ma)	$Ma_{100}Me_0$ to $Ma_{80}Me_{20}$
Dipyre	$c = 0.444$	$Ma_{80}Me_{20}$ to $Ma_{50}Me_{50}$
Mizzonite	$c = 0.442$	$Ma_{50}Me_{50}$ to $Ma_{20}Me_{80}$
Meionite	$c = 0.439$	$Ma_{20}Me_{80}$ to $Ma_0Me_{100}$

STRUC. Space group<sup>189</sup>  $I4/m$ ;  $a$  12.24,  $c$  7.59 Å. U.C. 2.

PHYS. CHAR. Crystals often long prismatic, vertically striated. Distinct 100 cleavage.  $G = 2.55$ – $2.65$ .  $H = 5.5$ – $6$ .  $F = 1100^\circ$ – $1200^\circ$ . Marialite is nearly insoluble in acids; meionite is decomposed by HCl.

OPT. PROP. Uniaxial negative with refringence ranging from that of quartz to about 1.60 and birefringence from about 0.005 to about 0.04. From Fig. 238 it may be inferred that pure  $3NaAlSi_3O_8 \cdot NaCl$  would be uniaxial positive. From Figs. 238 and 239 the following data may be tabulated:

	$N_O$	$N_E$	$N_O - N_E$	$G$ .
Marialite ( $Ma_{90}Me_{10}$ )	1.540	1.536	0.004	2.58
Dipyre ( $Ma_{65}Me_{35}$ )	1.558	1.545	0.013	2.635
Mizzonite ( $Ma_{35}Me_{65}$ )	1.582	1.555	0.027	2.70
Meionite ( $Ma_{10}Me_{90}$ )	1.600	1.563	0.037	2.75

For scapolite<sup>190</sup> with  $N_O = 1.5769$ ,  $N_E = 1.5556$ , dispersion,  $G - B$ , for  $N_O = 0.0166$ , for  $N_E = 0.015$ .

<sup>188</sup> J. W. Gruner: *Am. Mineral.*, XXIX, 172 (1944).

<sup>189</sup> A. Scherillo: *Min. Abst.*, VI, 287 (1936).

<sup>190</sup> C. J. Payne: *Min. Abst.*, VII, 518 (1940).



It is evident that the specific gravity, refringence, and birefringence all increase with increase of lime and alumina. However, variations from this series are common; their effects are known only approximately.

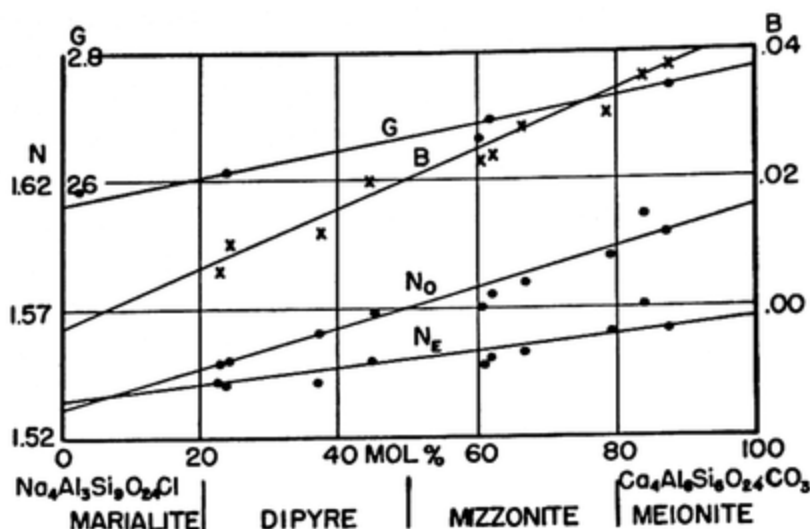


FIG. 238. Properties of the scapolite series.

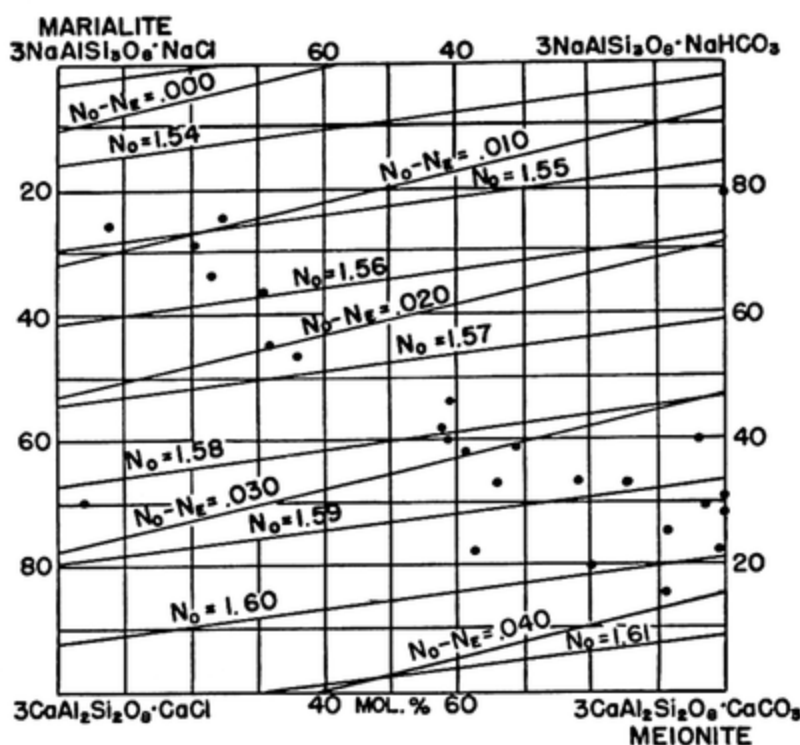


FIG. 239. Properties of the scapolite system. Each dot represents an analysis.

Increase of  $CO_3$  (forming  $NaHCO_3$ ) seems to raise the birefringence; the sulfate radical seems to reduce the birefringence by lowering  $N_0$  about 0.004 for each weight per cent of  $SO_3$ ;  $KOH$  seems to lower the index about 0.005 and the specific gravity about 0.02 for each per cent of  $K_2O$ .

Scapolite in mass is white, gray, bluish, greenish, reddish, black, color being due to stain. Colorless in section.

**INCL.** Inclusions are commonly abundant and may occupy more space than the enclosing mineral. In limestone they may be calcite or carbonaceous matter, though the latter may be lacking elsewhere in the rock. Other inclusions may be quartz, mica, feldspar, amphibole, garnet, etc. In mica schists the inclusions are commonly mica, tourmaline, rutile, actinolite, etc.; these may be oriented parallel with the vertical axis of the scapolite. In contact rocks the inclusions may be mica, pyroxene, tourmaline, etc.; they are usually unoriented.

**ALTER.** Common alteration products are mica, clinochlore, calcite, quartz, chabazite, and stilbite. By recrystallization under anamorphic conditions, scapolite may be changed to a mixture of forsterite and spinel.

**OCCUR.** Scapolite is found in schists and in contact rocks, both exomorphosed sediments and endomorphosed igneous rocks. Found at Pargas, Finland; Bamle, Norway; Ariège, France; Bolton, Massachusetts; etc.

**DIAG.** Scapolite differs from quartz in optic sign (in all known cases), in the presence of cleavage and common inclusions, and in stronger birefringence (except marialite).

## CANCRINITE

HEXAGONAL PYRAMIDAL  $\text{Na}_3\text{Ca}\{\text{CO}_3(\text{OH})_2\}\text{Si}_3\text{Al}_3\text{O}_{12}$   
 $c/a = 0.422$

**COMP.** Cancrinite varies much in composition.  $\text{CO}_3$  may be replaced by  $\text{SO}_4$  or  $\text{Cl}$ ;  $\text{Ca}$  by  $\text{NaH}$ ,  $\text{KH}$ , etc. Names which seem to apply to end-members include *cancrinite proper* =  $3\text{NaAlSiO}_4 \cdot \text{Ca}[\text{CO}_3, (\text{OH})_2]$ , *microsommit* =  $3\text{NaAlSiO}_4 \cdot \text{Ca}(\text{Cl}, \text{OH})_2$ , *wischnewite* =  $3\text{NaAlSiO}_4 \cdot (\text{HNaSO}_4, \text{NaOH})$ , *davyne* =  $3\text{NaAlSiO}_4 \cdot (\text{HKCO}_3, \text{KOH})$ , *natrodavyne* =  $3\text{NaAlSiO}_4 \cdot (\text{HNaCO}_3, \text{NaOH})$ , and *sulfatic cancrinite* =  $3\text{NaAlSiO}_4 \cdot [\text{Ca}\{\text{SO}_4, (\text{OH})_2\}]$ .

**STRUC.** Space group  $^{191}C6_3$ ;  $a$  12.75,  $c$  5.18 Å. U.C. 2.

**PHYS. CHAR.** Crystals prismatic, rare, with perfect  $10\bar{1}0$  cleavages.  $H. = 5-6$ .  $G. = 2.42-2.5$ .  $F. = 2$  with intumescence. Effervesces and gelatinizes with acids.

**OPT. PROP.** Uniaxial negative with  $N_O = 1.493-1.524$ ,  $N_E = 1.491-1.502$ ,  $N_O - N_E = 0.023-0.029$ ; see Fig. 240. With increasing  $K$  and  $\text{SO}_4$  the birefringence passes through zero, changing the optic sign to positive, and the indices are:  $N_O = 1.489-1.530$ ,  $N_E = 1.488-1.535$ ,  $N_E - N_O = 0.0007$  to  $0.008$ . Colorless, white, or rarely blue (wischnewite).

**ALTER.** Cancrinite alters to natrolite in rare cases.

**OCCUR.** Cancrinite is apparently a primary constituent of certain sodic igneous rocks; also a common alteration product of nepheline. Found at Miask in the Urals; Detrol, Transylvania; Litchfield, Maine; etc.

**DIAG.** Cancrinite differs from nepheline in its much stronger birefringence, its ready fusibility, and effervescence; from scapolite in cleavage; from calcite in cleavage and much weaker birefringence; and from thomsonite by its uniaxial character.

<sup>191</sup> S. Kozu and K. Takane: *Proc. Imp. Acad. Japan*, IX, 56, 105 (1933).

**Leifite** ( $Na_2FSi_5AlO_{12}?$ ) is hexagonal with  $c/a = 0.344$ . Point group  $^{192} D_3, D_{3d}$ , or  $C_{3v}$ ;  $a$  14.34,  $c$  4.93 Å. U.C. 4? Crystals acicular, deeply striated, with distinct prismatic cleavage.  $H. = 6$ .  $G. = 2.57$ .  $F. = \text{easy}$ . Insoluble in acids. Uniaxial positive with  $N_O = 1.5177$ ;  $N_E = 1.5224$ ,  $N_E - N_O = 0.0044$  (calc.), 0.0047 (obs.). Colorless. Inclusions may be abundant, in some cases arranged in vertical lines.

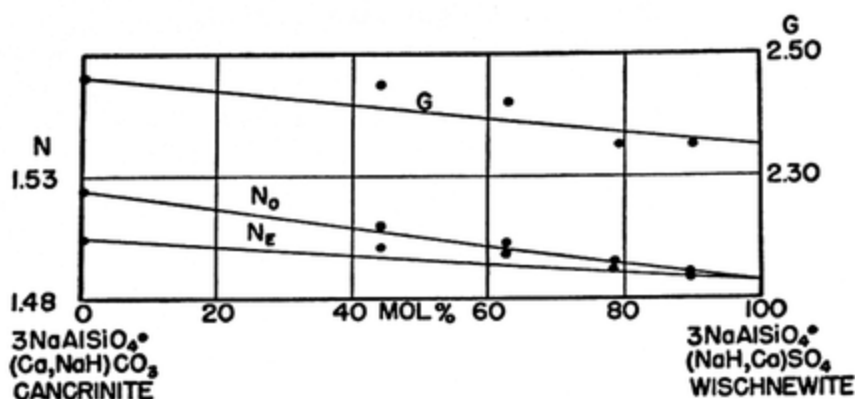


FIG. 240. Properties of the cancrinite-wischnewite series.

Found in pegmatite with microcline, acmite, zinnwaldite, calcite, at Narsarsuk, Greenland.

**Cymrite** ( $BaOHSi_3AlO_8$ ) is hexagonal with  $^{193} c/a = 1.442$ .  $a$  5.32,  $c$  7.67 Å. Crystals small prisms or thin plates. Perfect basal and good prismatic cleavage.  $G. = 3.41$ . Uniaxial negative with  $N_O = 1.6225$ ,  $N_E = 1.6125$ ,  $N_O - N_E = 0.010$ . Colorless. Found in Carnarvonshire, Wales.

**DATOLITE** MONOCLINIC PRISMATIC  $^{194}$   $CaOHSiBO_4$   
 $a:b:c = 1.265:1:0.633$   $\beta = 90^\circ 9'$

STRUC. Space group  $P2_1/c$ ;  $a$  9.64,  $b$  7.62,  $c$  4.82 Å. U.C. 4.

PHYS. CHAR. Crystals short prismatic, with {001} or highly modified pyramidal forms, without distinct cleavage.  $H. = 5-5.5$ .  $G. = 2.9-3.0$ .  $F. = 2-2.5$ . Gelatinizes with HCl.

OPT. PROP. The optic plane is 010;  $Z \wedge c = +1^\circ$  to  $+4^\circ$ , with dispersion. See Fig. 241.  $(- )2V = 74^\circ$ ,  $r > v$  weak.  $N_X = 1.626$ ,  $N_Y = 1.6535$ ,  $N_Z = 1.670$ ,  $N_Z - N_X = 0.044$ . Color white or tinted; colorless in section.

OCCUR. Datolite is always secondary; often associated with zeolites and calcite in amygdules; also in veins, etc. Found at Arendal, Norway; Utö, Sweden; Roaring Brook, Connecticut; Bergen Hill, New Jersey; etc.

DIAG. It usually has distinctive crystal forms; it contains boron, but not aluminum.

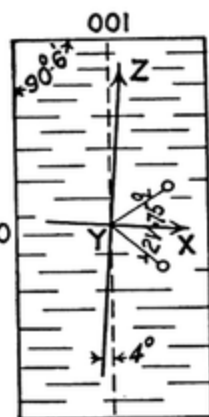


FIG. 241. The optic orientation of datolite.

<sup>192</sup> B. Gossner and F. Mussgnug: *Cent. Min.*, 1927A, 221.

<sup>193</sup> W. C. Smith, F. A. Bannister, and M. H. Hey: *Am. Mineral.*, XXXIV, 614 (1949). Cymru, the Welsh name for Wales, is pronounced kumry.

<sup>194</sup> B. Gossner and F. Mussgnug: *Zeit. Krist.*, LXX, 171 (1929).

## GADOLINITE

## MONOCLINIC PRISMATIC



$$a:b:c = 0.618:1:1.311 \quad \beta = 90^\circ 33'$$

COMP. Ce, La, Di, Fe<sup>III</sup>, Ca, Na, H often present; e.g., 23.4 Ce<sub>2</sub>O<sub>3</sub>. Also H<sub>2</sub>O.

STRUC. Space group <sup>195</sup>  $P2_1/c$ ;  $a$  4.65,  $b$  7.53,  $c$  9.87 Å. U.C. 2.

PHYS. CHAR. Crystals rough prismatic, without cleavage.  $H. = 6.5-7$ .  $G. = 4.0-4.6$ , decreasing with alteration. Gelatinizes with HCl.

OPT. PROP. The optic plane is 010;  $Z \wedge c = +6^\circ$  to  $+10^\circ$  (green variety) and  $+12^\circ$  to  $+14^\circ$  (brown variety).  $(+ )2V = 85^\circ$  ca.,  $r < v$  strong. See Fig. 242.  $N_X = 1.772-1.780$  (Larsen <sup>41</sup>),  $N_Y = 1.78$  ca.,  $N_Z = 1.777-1.785$ ,  $N_Z - N_X = 0.010$  ca. (variable—strong to zero, due to alteration).  $N_X = 1.801$ ,  $N_Y = 1.812$ ,  $N_Z = 1.824$ ,  $N_Z - N_X = 0.023$  (Vogt <sup>96</sup>). Color black, greenish, brown; in thin section green or brown but not pleochroic; in thick section  $X =$  olive green,  $Y = Z =$  grass green.

ALTER. Gadolinite alters easily to an amorphous ("metamict") state with  $N = 1.78$  ca.

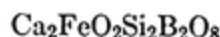
OCCUR. It is found chiefly in pegmatite often with fluorite at Falun and Ytterby, Sweden; Baveno, Italy; in Llano County, Texas, etc.

DIAG. It is characterized by variable birefringence, high relief, lack of cleavage and of pleochroism, large optic angle, and presence of rare earths.

*Calciogadolinite* <sup>197</sup> is a variety containing 11.9 CaO; it has  $G. = 4.5$ ,  $N_X = 1.765$ ,  $N_Y = 1.774$ ,  $N_Z = 1.787$ ,  $N_Z - N_X = 0.022$ . Strongly pleochroic with  $X =$  light brown,  $Y =$  light yellow,  $Z =$  dark brown. Found in pegmatite at Tadati, Japan.

## KOMILITE

## MONOCLINIC



$$a:b:c = 0.625:1:0.642 \quad \beta = 90^\circ 22'$$

COMP. A little Al, Fe<sup>III</sup>, Na, etc., may be present.

PHYS. CHAR. Crystals {001} tablets or pseudopyramidal with {110} and {012} or  $\{\bar{1}11\}$ . Twinning on 001; no distinct cleavage.  $H. = 5$ .  $G. = 3.36$ .  $F. = 2$  to a black glass. Gelatinizes with HCl.

OPT. PROP. The optic plane and  $Z$  are normal to 010;  $Y \wedge c = -1^\circ$ . See Fig. 243.  $(+ )2V = 80^\circ$ ,  $r > v$  distinct, with very strong horizontal dispersion.  $N_X = 1.715$ ,  $N_Y = 1.725$ ,  $N_Z = 1.738$ ,  $N_Z - N_X = 0.023$ . Color black to dark brown. No distinct pleochroism in thin section; in thick section  $X =$  bluish green,  $Y =$  deep brownish red to brownish gray,  $Z =$  smoky gray or brownish yellow, and  $Y > X > Z$ .

ALTER. Homilite is often altered to an amorphous ("metamict") condition with  $N = 1.64$  ca.; an altered border may have

<sup>195</sup> R. L. Parker et al.: *Schw. Min. Pet. Mit.*, XX, 11 (1940).

<sup>196</sup> T. Vogt: *Vid.-Selsk. Skr. Kristiania, Mat.-Nat. Kl.*, I, 17 (1922); *Min. Abst.*, II, 25 (1923).

<sup>197</sup> T. Nakai: *Min. Abst.*, VII, 264 (1939).

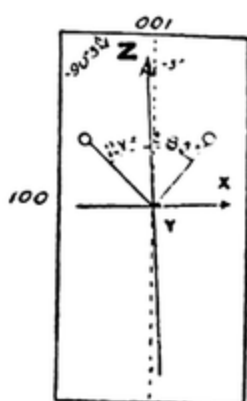


FIG. 242. The optic orientation of gadolinite.

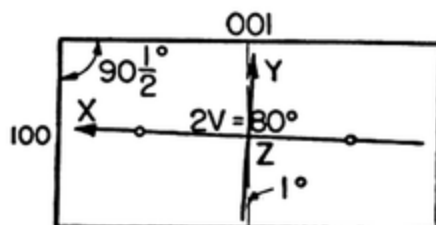


FIG. 243. The optic orientation of homilite.

variable properties, as follows:  $(+ )2E = 0^\circ - 78^\circ$ ,  $2V = 0^\circ - 45^\circ$ ,  $r > v$  or  $r < v$  very strong,  $N_Y = 1.665 - 1.630$ ,  $N_Z - N_X = 0.02 \pm$ . Color yellow.

**OCCUR.** It is found in pegmatite at Langesundfiord in Norway.

**DIAG.** It is characterized by high relief, amorphous alteration product, no cleavage, greenish color, and lack of pleochroism in thin section.

**Duplexite**<sup>198</sup>  $[Ca_6(OH)_6Si_{14}Al_2Be_4O_{40}]$  is probably monoclinic. It has two good cleavages at right angles. Crystals are pearly aggregates or squarish plates (on beryl).  $X \wedge c = 2 - 5^\circ$ .  $(+ )2V = 22^\circ$ ,  $N_X = 1.582$ ,  $N_Y = 1.584$ ,  $N_Z = 1.593$ ,  $N_Z - N_X = 0.011$ . Colorless. Found in Londonderry, Western Australia.

## B. PHYLLOSILICATES (SHEETS OF TETRAHEDRONS)

### 1. Type formula $A_m(B_2X_5)_n$

The phyllosilicates have  $SiO_4$  groups which are united to other  $SiO_4$  groups by having three oxygen atoms in common, as illustrated in Fig. 130. No  $SiO_4$  group has more than one oxygen atom in common with any one other  $SiO_4$  group; each  $SiO_4$  group is thus linked to three other  $SiO_4$  groups. This results in forming layers; minerals of this structure are characterized by eminent cleavage parallel with these layers.

#### (a) WITHOUT ADDITIONAL ANIONS—ANHYDROUS

**Gillespite** ( $Fe''BaSi_4O_{10}$ ) is ditetragonal dipyramidal with  $c/a = 2.141$ . Space group <sup>1</sup>  $P4/ncc$ ;  $a$  7.495,  $c$  16.05 Å. U.C. 4. Perfect 001 and poor 100 cleavages.  $H. = 3$ .  $G. = 3.4$ .  $F. =$  easy. Leached by HCl, leaving  $SiO_2$  and  $H_2O$  [then  $G. = 1.8 - 2.0$ ; uniaxial negative <sup>2</sup> with  $N_O = 1.449$  (1.465),  $N_E = 1.441$  (1.455),  $N_O - N_E = 0.008$  (0.010)]. Gillespite is uniaxial negative with  $N_O = 1.621$ ,  $N_E = 1.619$ ,  $N_O - N_E = 0.002$ . Color rose red with  $O =$  pale pink,  $E =$  deep rose red. Found with celsian, quartz, etc., at Dry Delta, Alaska, and Incline, California.

#### EUCLASE

#### MONOCLINIC PRISMATIC <sup>3</sup>

#### $BeSiAlO_4(OH)$

$$a:b:c = 0.324:1:0.334 \quad \beta = 100^\circ 16'$$

**STRUC.** Space group  $P2_1/c$ ;  $a$  4.62,  $b$  14.24,  $c$  4.75 Å. U.C. 4.

**PHYS. CHAR.** Crystals prismatic with many faces. Perfect 010 and poor 110 and 001 cleavages. Slight vertical elongation.  $H. = 7.5$ .  $G. = 3.0 - 3.1$ .  $F. = 5.5$ . Insoluble.

**OPT. PROP.** The optic plane is 010;  $Z \wedge c = -41^\circ$ .  $(+ )2V = 50^\circ \pm$ ,  $r > v$ . See Fig. 244.  $N_X = 1.651$ ,  $N_Y = 1.655$ ,  $N_Z = 1.671$ ,  $N_Z - N_X = 0.020$ . Again:<sup>4</sup>

<sup>198</sup> H. P. Rowledge and J. D. Hayton: *J. Roy. Soc. W. Australia*, XXXIII, 45 (1948); *Min. Abst.*, X, 508 (1949).

<sup>1</sup> A. Pabst: *Am. Mineral.*, XXVIII, 372 (1943).

<sup>2</sup> W. T. Schaller: *Am. Mineral.*, XIV, 319 (1929).

<sup>3</sup> J. Biscoe and B. E. Warren: *Zeit. Krist.*, LXXVI, 292 (1933).

<sup>4</sup> A. Cavinato: *Min. Abst.*, IV, 522 (1931).

(+) $2V = 46^\circ 38'$ ,  $N_X = 1.6528$ ,  $N_Y = 1.6560$ ,  $N_Z = 1.6725$ ,  $N_Z - N_X = 0.0197$ .

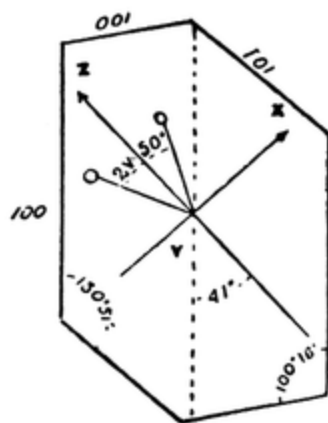


FIG. 244. The optic orientation of euclase.

Colorless, pale green, or blue; may be colored and pleochroic in thick plates, with variable orientation of colors.

**OCCUR.** Euclase is found in chlorite schist in Minas Geraes, Brazil, and in the Austrian Alps; also in granite, etc.

**DIAG.** It is distinguished by its crystal form, perfect cleavage, positive elongation with very large extinction angle, high relief, association with topaz, and content of Be.

**Sanbornite**<sup>5</sup> ( $\text{Ba}_2\text{Si}_4\text{O}_{10}$ ) is triclinic with perfect 001 and poor 010 cleavages; polysynthetic twinning on 010.  $H. = 5$ .  $G. = 4.19$ . The optic plane is nearly normal to 010;  $Z$  is nearly normal to 001. Extinction angle on 001 is  $3.5^\circ$  and on 010 it is  $5.5^\circ$ .  $(- )2V = 66^\circ$ , calc.  $N_X = 1.597$ ,  $N_Y = 1.616$ ,  $N_Z = 1.624$ ,  $N_Z - N_X = 0.027$ . Colorless. Found with celsian, quartz, etc., at Incline, California. The artificial substance is said to be orthorhombic.<sup>6</sup>

### (a) WITHOUT ADDITIONAL ANIONS—HYDROUS

**Okenite** ( $\text{Ca}_2\text{Si}_4\text{O}_{10} \cdot 4\text{H}_2\text{O}$ ) is triclinic with  $\alpha = 122^\circ 54'$ ,  $\beta = 67^\circ 46'$ ,  $\gamma = 50^\circ 10'$ ; fibrous interlaced masses; also {010} laths with perfect 010 cleavage, appearing curved in aggregates; twinning on 010 and axis  $c$ . Elastic.  $H. = 5$ .  $G. = 2.28-2.33$ .  $F. = 2.5$ . Gelatinizes with  $\text{HCl}$ . Extinction parallel to  $c$  in 010, but oblique in all other directions; thus, for light moving parallel to 010 and normal to  $c$ , the extinction is at  $25^\circ$  to the 010 cleavage. Extinction in the vertical zone<sup>7</sup> may reach  $34^\circ$ . Indices vary notably (owing to variable tenor of water?),  $N_Z$  ranging from 1.536 (Hey<sup>8</sup>) to 1.553 (Tilley<sup>9</sup>). Color white or pale; colorless in section. Found in amygdules in basalt with apophyllite, heulandite, etc., as near Bombay, India. Characterized by parallel extinction in plates lying on 010, but markedly oblique extinction in aggregates; also by positive elongation.

### (b) WITH ADDITIONAL ANIONS—ANHYDROUS

**Narsarsukite**<sup>10</sup> [ $\text{Na}_2(\text{Ti,Fe})(\text{O,OH,F})\text{Si}_4\text{O}_{10}$ ] is ditetragonal dipyramidal with  $c/a = 0.735$ ;  $a$  10.74,  $c$  7.90 Å. U.C. 4. Crystals {001} tablets or short prismatic with perfect 100 cleavage.  $H. = 5.5-7.5$ .  $G. = 2.75$ . Easily fusible. Soluble only in  $\text{HF}$ . Uniaxial positive with  $N_O = 1.604$ ,  $N_E = 1.625$ ,  $N_E - N_O = 0.021$  (Graham<sup>11</sup>);  $N_O = 1.609$ ,  $N_E = 1.630$ ,  $N_E - N_O = 0.021$  (Larsen<sup>12</sup>);  $N_O = 1.608$ ,  $N_E = 1.653$ ,

<sup>5</sup> A. F. Rogers: *Am. Mineral.*, XVII, 161 (1932).

<sup>6</sup> P. Eskola: *Am. Jour. Sci.*, CCIV, 331 (1922).

<sup>7</sup> O. B. Bøggild: *Min. Abst.*, II, 59 (1923).

<sup>8</sup> M. H. Hey: *Mineral. Mag.*, XXIII, 81 (1932).

<sup>9</sup> C. E. Tilley and A. R. Alderman: *Mineral. Mag.*, XXIII, 513 (1934).

<sup>10</sup> B. E. Warren and C. R. Amberg: *Am. Mineral.*, XIX, 546 (1934).

<sup>11</sup> W. A. P. Graham: *Am. Mineral.*, XX, 598 (1935).

<sup>12</sup> E. S. Larsen: *U. S. Geol. Surv. Bull.* 679 (1921) and 848 (1934).



$N_E - N_O = 0.045$  (Graham<sup>11</sup>). Colorless, yellow, or brown; not pleochroic or O = colorless, E = honey yellow. Found at Narsarsuk, Greenland, and also in the Sweet Grass Hills, Montana.

**PYROSMALITE**

HEXAGONAL SCALENOHEDRAL  $(Mn,Fe)_8(OH,Cl)_{10}Si_6O_{15}$   
 $c/a = 0.536$

COMP. The Mn end-member is called *friedelite*; the series is not well known; small amounts of Mg, Ca, Zn may be present.

STRUC. Space group <sup>13</sup>  $C\bar{3}m$ ;  $a$  13.44,  $c$  7.20 Å. U.C. 4.

PHYS. CHAR. Crystals hexagonal plates with perfect basal cleavage. H. = 4–5. G. = 3.06–3.19. F. = 3–4 to black glass. Gelatinizes with HCl.

OPT. PROP. Uniaxial negative with strong birefringence. Also biaxial with  $2V$  = small in some crystals of *friedelite*.

Friedelite	$N_O = 1.654$	$N_E = 1.625$	$N_O - N_E = 0.029$	Bauer <sup>14</sup>
	$N_O = 1.664$	$N_E = 1.629$	$N_O - N_E = 0.035$	Larsen <sup>12</sup>
Pyrosmalite	$N_O = 1.675$	$N_E = 1.636$	$N_O - N_E = 0.039$	Larsen <sup>12</sup>
	$N_O = 1.682$	$N_E = 1.647$	$N_O - N_E = 0.035$	Flink <sup>16</sup>

Color of *friedelite* rose red to colorless; in sections 0.5 mm. thick O = dark reddish brown, E = very pale yellow. Color of *pyrosmalite* dark green to pale brown; also gray to pale green, brown apparently due to surface oxidation; thick plates pleochroic with O > E. Both are (nearly) colorless in thin section.

OCCUR. *Pyrosmalite* is found in manganese and iron mines, as at Pajsberg, Sweden, and Franklin, New Jersey.

**Schallerite**  $[(Mn,Fe)_8(OH,Cl)_{10}(Si,As)_6O_{15}]$  is hexagonal (scalenohedral?). It may contain some Zn, Mg. Perfect basal cleavage. H. = 4.5–5. G. = 3.37. F. = 5–6. Decomposed by HCl. Uniaxial negative with  $N_O = 1.704$ ,  $N_E = 1.679$ ,  $N_O - N_E = 0.025$ . Color light brown in mass. Found at Franklin, New Jersey, in zinc ores. *Ferroschallerite* contains considerable iron and a little zinc; in it<sup>16</sup>  $(Mn + Zn):Fe = 2:1$ . G. = 3.44.  $N_O = 1.718$ ,  $N_E = 1.700$ ,  $N_O - N_E = 0.018$ .

**Zeophyllite**  $[Ca_8(OH,F)_{10}Si_6O_{15}]$  is hexagonal (scalenohedral?) with  $c/a = 2.245$ . ( $c/a = 1.71$ —Koechlin.<sup>17</sup>) Perfect basal cleavage. H. = 3. G. = 2.76. F. = easy. Soluble in HCl. Uniaxial negative with  $N_O = 1.565$ ,  $N_E = 1.560$ ,  $N_O - N_E = 0.005$ . Also biaxial  $2V$  reaching  $27^\circ$ ,  $r < v$ . Colorless to greenish. Found with *natrolite*, etc., in amygdules, as at Radzein and Leipa, Bohemia.

**PREHNITE**

ORTHORHOMBIC PYRAMIDAL

$Ca_2Al(OH)_2Si_3AlO_{10}(?)$

$a:b:c = 0.842:1:3.357$

COMP.  $Fe'''$  may proxy for part of the Al.

STRUC. Space group <sup>18</sup>  $P2cm$ ;  $a$  4.65,  $b$  5.52,  $c$  18.53 Å. U.C. 2.

<sup>13</sup> B. Gossner and F. Mussgnug: *Zeit. Krist.*, LXXVI, 525 (1931).

<sup>14</sup> L. H. Bauer and H. Berman: *Am. Mineral.*, XIII, 341 (1928).

<sup>15</sup> G. Flink: *Ark. Kemi Min. Geol.*, VI, 21 (1917).

<sup>16</sup> C. Palache: *U. S. Geol. Surv. Prof. Paper* 180, 90 (1937).

<sup>17</sup> R. Koechlin: *Cent. Min.*, 1934A, 256.

<sup>18</sup> B. Gossner and F. Mussgnug: *Cent. Min.*, 1931A, 419; see also ref. 21.

**PHYS. CHAR.** Crystals {001} tablets or prismatic; often columnar or lamellar massive. Distinct 001 cleavage.  $H. = 6-6.5$ .  $G. = 2.80-2.95$ .  $F. = 2$  with intumescence to a blebby enamel. Slowly soluble in HCl.

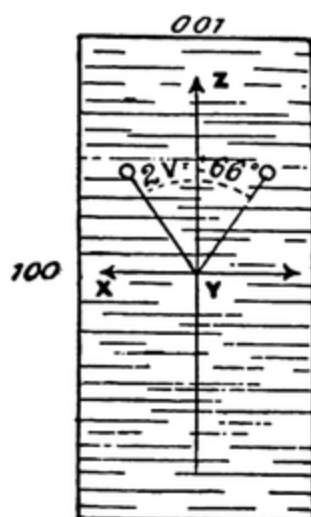


FIG. 245. The optic orientation of prehnite.

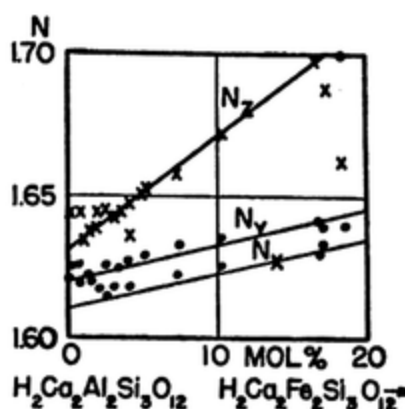


FIG. 246. Properties of prehnite.

**OPT. PROP.** The optic plane is 010;  $X = a$ . See Fig. 245.  $(+)2V = 66^\circ-69^\circ$  (also small). Elongation negative when tabular, positive when prismatic. Data follow (see also Fig. 246):

	Taylor <sup>19</sup>	Fraser <sup>20</sup>	Nuffield <sup>21</sup>	Lacroix <sup>22</sup>	Shannon <sup>23</sup>	Poitevin <sup>24</sup>
$Fe_2O_3 = ?$		1.20	1.03	?	2.10	6.89
$(+)2V = 65^\circ$		$64^\circ$	$69^\circ$	?	Mod.	$67.5^\circ$ calc.
$N_X = 1.614$		1.612	1.615	1.616	1.626	1.632
$N_Y = 1.621$		1.618	1.624	1.626	1.629	1.642
$N_Z = 1.641$		1.642	1.644	1.649	1.652	1.665
$N_Z - N_X = 0.027$		0.030	0.029	0.033	0.026	0.033

Color pale green, gray, white; colorless in thin section.

Optic anomalies are not uncommon. Some sections show fine twinning lamellae like those of microcline; basal sections may show bands parallel and normal to 100, the optic plane being at right angles in the two sets of bands; it is believed that these bands may be submicroscopic in some cases causing the optic angle to appear much smaller, the dispersion to be abnormal ( $r < v$ , or even crossed, strong), and the incomplete extinction with abnormal interference colors.

**INCL.** The green color may be due to abundant inclusions of chlorite; limonite gives a yellowish tint; asbestos gives a white color.

<sup>19</sup> J. H. Taylor: *Am. Mineral.*, XX, 120 (1935).

<sup>20</sup> D. M. Fraser and R. D. Butler: *Am. Mineral.*, XXIII, 583 (1938).

<sup>21</sup> E. W. Nuffield (*U. Toronto Geol. Stud.*, XLVIII, 49, 1943) gives  $a$  4.60,  $b$  5.46,  $c$  18.44 Å.

<sup>22</sup> A. Lacroix: *Minéraux des Roches*, 1888, 317.

<sup>23</sup> E. V. Shannon: *U. S. Nat. Mus. Bull.* 131, 330 (1926).

<sup>24</sup> E. Poitevin: *Geol. Surv. Canada, Bull.* 46 (1927).

**OCCUR.** Prehnite is found chiefly in cavities in basalts, often associated with zeolites, calcite, datolite, pectolite, etc. It is also found in schists, amphibolites, pegmatites, and veins. Usually secondary.

**DIAG.** It differs from other colorless alteration products by its high relief and strong birefringence. Thomsonite is fibrous with  $\pm$  elongation; lawsonite has more cleavages and weaker birefringence; datolite has stronger birefringence and opposite sign; andalusite, topaz, and wollastonite have weaker birefringence.

**Bementite**<sup>25</sup>  $[Mn_5(OH)_6Si_4O_{10}]$  is orthorhombic; crystals fibrous or lamellar with micaceous 001 and perfect 010 and 100 cleavages.  $H. = 6$ .  $G. = 3.1$ .  $F. = 3.5$ . Soluble in HCl. Acute bisectrix X normal to 001; Y or Z parallel with fibers. Nearly uniaxial.  $(- )2E =$  nearly  $0^\circ$ ,  $N_X = 1.602$  to  $1.624$ ,  $N_Y = N_Z = 1.632$  to  $1.650$ ,  $N_Z - N_X = 0.030$  to  $0.026$ . Color brown, yellow, gray; darkens on weathering; pleochroism very weak with  $X < Y = Z$ . Found in anamorphosed manganese deposits, as at Franklin, New Jersey.

**Ekmannite**<sup>26</sup> is chemically related to bementite but seems to vary considerably and needs further study. Perfect 001 cleavage.  $G. = 2.79$ .  $X = c$ .  $(- )2V = 0^\circ$  or very small,  $N_X = 1.582$ ,  $N_Y = N_Z = 1.670$ ,  $N_Z - N_X = 0.088$ . Color gray with  $X =$  colorless,  $Y = Z =$  pale green. A darker-colored type with 7.07  $Fe_2O_3$  and 1.65  $Al_2O_3$  has  $N_X = 1.581$ ,  $N_Y = N_Z = 1.637$ ,  $N_Z - N_X = 0.056$ . Color black with  $X =$  nearly colorless,  $Y = Z =$  dark (greenish) brown. Found in ore deposits, at Grythyttan, Sweden.

**Nordite**<sup>27</sup>  $[Na_6(Sr,Mn,Ca,Mg)_4(La,Nd,Ce,Y)_4O_9Si_{12}O_{30}]$  is orthorhombic with  $a:b:c = 0.730:1:0.527$ . Usually lamellar. Good 100 cleavage.  $H. = 5-6$ .  $G. = 3.43$ .  $X = a$ ;  $Y = b$ .  $(- )2V = 31.5^\circ$ ,  $N_X = 1.619$ ,  $N_Y = 1.63-1.64$ ,  $N_Z = 1.642$ ,  $N_Z - N_X = 0.023$ . Color light brown; streak white. Found in pegmatite on the Kola peninsula, U.S.S.R.

## PYROPHYLLITE

### MONOCLINIC PRISMATIC

$$a:b:c = 0.580:1:2.095 \quad \beta = 99^\circ 55'$$

**STRUC.** Space group<sup>28</sup>  $C2/c$ ;  $a$  5.15,  $b$  8.88,  $c$  18.60 Å. U.C. 4.

**PHYS. CHAR.** Lamellar masses with perfect 001 cleavage, giving flexible and inelastic lamellae.  $H. = 1-1.5$ .  $G. = 2.84$ .  $F. = 6$ , after much increase in volume.

**OPT. PROP.** The acute bisectrix X is normal to the basal cleavage and Z is parallel to the elongation of the blades. See Fig. 247.  $(- )2V = 53^\circ-60^\circ$ ,  $r > v$ , weak.  $N_X = 1.552$ ,  $N_Y = 1.588$ ,  $N_Z = 1.600$ ,  $N_Z - N_X = 0.048$ . Colorless or tinted.

**OCCUR.** Pyrophyllite is abundant locally in some schists, as in North Carolina. It is used to make slate pencils.

**DIAG.** It differs from talc and muscovite in its larger optic angle and from kaolinite in its much stronger birefringence.

<sup>25</sup> *Caryopilite* is the same; see J. T. Pardee *et al.*: *Jour. Wash. Acad. Sci.*, XI, 25 (1921). *Ectropite* of Flink (*Geol. För. Förh.*, XXXIX, 426, 1917) is considered the same as bementite by Larsen (*Am. Mineral.*, X, 418, 1925); it has  $H. = 4$ ,  $G. = 2.46$ ,  $N_Z = N_Y = 1.633$ ,  $N_X = 1.608$ .

<sup>26</sup> J. Jakob: *Schw. Min. Pet. Mit.*, III, 237 (1923); IV, 51 (1924).

<sup>27</sup> V. I. Gerasimovsky: *Min. Abst.*, VIII, 279 (1942).

<sup>28</sup> S. B. Hendricks: *Zeit. Krist.*, XCIX, 264 (1938).

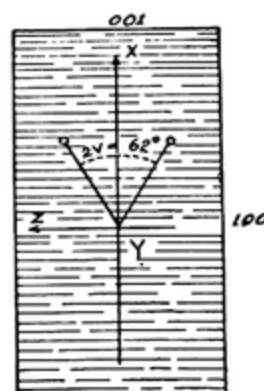
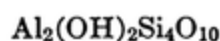
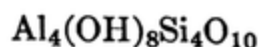


FIG. 247. The optic orientation of pyrophyllite.

**KAOLINITE**

TRICLINIC PINACOIDAL



$a:b:c = 0.576:1:0.830$

$\alpha = 91^\circ 48'$

$\beta = 104^\circ 30'$

$\gamma = 90^\circ$

COMP. The ratio between Al and Si seems to be somewhat variable, perhaps to that of *anauxite*,  $\text{Al}_3(\text{OH})_5\text{Si}_4\text{O}_{10} \cdot \text{H}_2\text{O}$ ? See Fig. 248.

STRUC. Space group  $^{29} P\bar{1}$ ;  $a$  5.14,  $b$  8.93,  $c$  7.37 Å. U.C. 1.

PHYS. CHAR. Crystals pseudohexagonal basal scales often in curved vermicular groups with twinning as in mica. Compact, with greasy

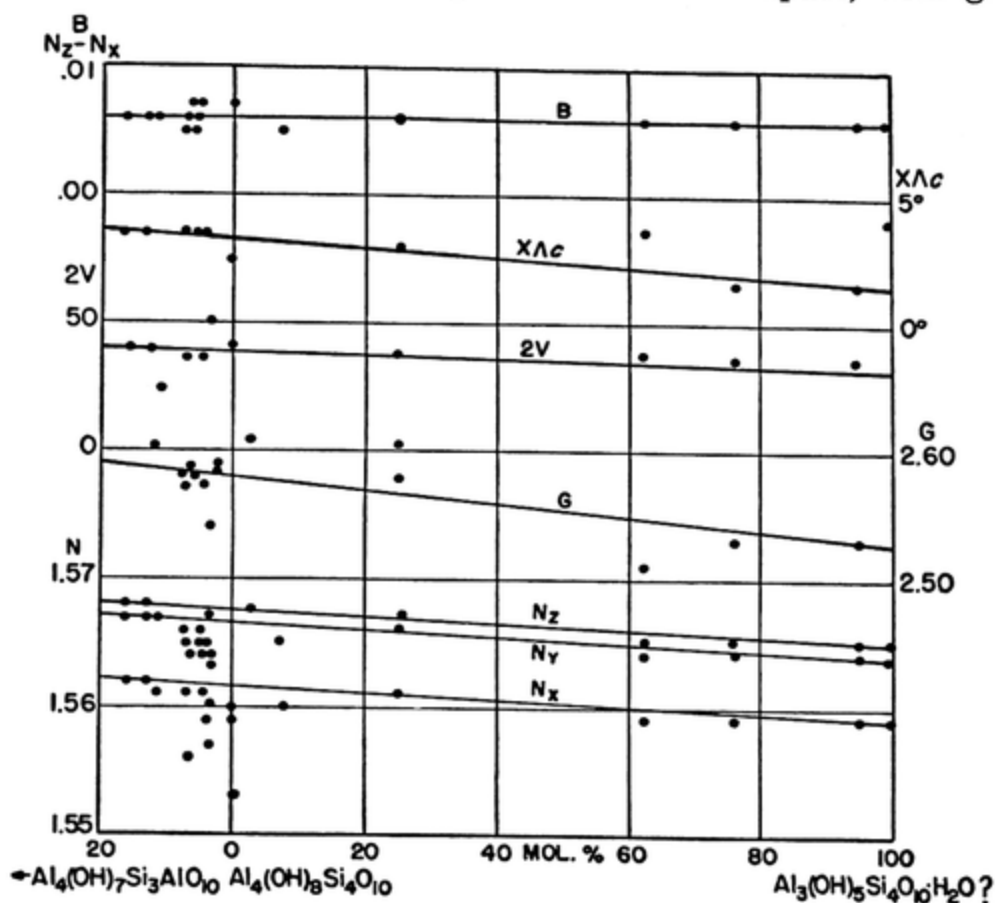


FIG. 248. Properties of kaolinite.

feel. Perfect 001 cleavage; laminae flexible, but not elastic.  $H. = 2-2.5$ .  $G. = 2.61$ .  $F. = 7$ . Insoluble in acids. Loses water at about  $450^\circ$ .

OPT. PROP. The optic plane and  $Z$  are normal to 010;  $X \wedge \perp 001 = 3^\circ$ .  $(- )2V = 20^\circ-55^\circ$ ; mean value about  $42^\circ$ ;  $r > v$  weak.  $N_x = 1.560$  (1.553-1.563),  $N_y = 1.565$  (1.559-1.569),  $N_z = 1.566$  (1.560-1.570),  $N_z - N_x = 0.006-0.007$ . See Fig. 248. With more water (18.7%)  $N_x = 1.526$ ,  $N_y = ?$ ,  $N_z = 1.543$ ,  $N_z - N_x = 0.017$ . Colorless or rarely tinted and pleochroic with  $X =$  colorless or cream buff,  $Y = Z =$  cream buff or dark olive buff.

<sup>29</sup> G. W. Brindley and K. Robinson: *Nature*, CLVI, 661 (1945); *Mineral. Mag.*, XXVII, 242 (1946). See also J. W. Gruner: *Zeit. Krist.*, LXXXIII, 75 (1932).

**INVER.** Two other phases are known, called *dickite* and *nacrite*. Kaolinite has been synthesized at ordinary temperature, dickite at 350°; nacrite is probably stable at still higher temperatures. All three are found in nature.

**ALTER.** Several forms of kaolinite minus  $H_2O$ , that is,  $H_2Al_2Si_2O_8$ , have been made but their optic properties are unknown. Kaolinite absorbs dyes readily and thus becomes strongly pleochroic.

**OCCUR.** Kaolinite is the chief constituent of ordinary clay, which usually contains also quartz, limonite, etc. Kaolinite is a common alteration product of feldspar, feldspathoids, and other silicates.

**DIAG.** It differs from sericite, talc, pyrophyllite, leverrierite, and gibbsite by its weaker birefringence and infusibility.

**Dickite**  $[Al_4(OH)_8Si_4O_{10}]$  is monoclinic domatic with  $a:b:c = 0.575:1:3.327$ ,  $\beta = 96^\circ 49'$ . Space group  $^{30} Cc$ ;  $a$  5.15,  $b$  8.95,  $c$  28.68 Å. U.C. 4. Crystals basal scales with perfect 001 cleavage.  $H. = 2.5-3$ .  $G. = 2.62$ .  $F. = 7$ . Loses water at about 550°.  $Z = b$ ;  $Y \wedge a = +11^\circ$  to  $+20^\circ$  ( $3^\circ$  greater for red than for blue). See Fig. 249.  $(+ )2V = 68^\circ-80^\circ$ ,  $r < v$ .  $N_X = 1.560$ ,  $N_Y = 1.562$ ,  $N_Z = 1.566$ ,  $N_Z - N_X = 0.006$ . Extinction angle ( $Y \wedge a =$  trace of cleavage) distinctly greater in red than in violet light. Colorless. Does not readily absorb dyes. Found in ore deposits.

**Nacrite**  $[Al_4(OH)_8Si_4O_{10}]$  is monoclinic domatic  $^{30}$  with  $a:b:c = 0.575:1:3.331$ ,  $\beta = 91^\circ 43'$ . Space group  $Cc$ ;  $a$  5.15,  $b$  8.95,  $c$  28.70 Å. U.C. 4. Pseudo-hexagonal by twinning. Perfect 001 and good 010 and 110 cleavages.  $H. = 2.5-3$ .  $G. = 2.5$  ca.  $F. = 7$ , but exfoliates. Retains part of its water to 600° or more.  $Z = b$ ,  $Y \wedge a = 10^\circ-12^\circ$ .  $(- )2V = 40^\circ$ ,  $r > v$ ; also  $(+ )2V = 90^\circ$  ca.  $r < v$ ,  $N_X = 1.557$ ,  $N_Y = 1.562$ ,  $N_Z = 1.563$ ,  $N_Z - N_X = 0.006$ . With  $^{31} 0.34 Fe_2O_3$ :  $(- )2V = 80^\circ$ ,  $N_X = 1.560$ ,  $N_Y = 1.563$ ,  $N_Z = 1.566$ ,  $N_Z - N_X = 0.006$ ;  $Y \wedge a = 10^\circ-13^\circ$ . On dehydration  $N_Y$  is still 1.561 at 350°, 1.540 at 400°, 1.509 at 500°, then steadily increases to 1.528 at 800°. Colorless. Does not readily absorb dyes. Found in ore deposits, apparently formed under pneumatolytic conditions.

**Miloschite**  $[(Al,Cr)_4(OH)_8Si_4O_{10}]$  is probably closely related to kaolinite. It is lamellar to tabular.  $H. = 2.5$ .  $G. = 2.1$ .  $F. = 7$ . Almost insoluble in HCl. Good basal cleavage. Extinction slightly inclined.  $(- )2V$  near  $90^\circ$ ,  $N_X = 1.552$ ,  $N_Y = 1.556$ ,  $N_Z = 1.559$ ,  $N_Z - N_X = 0.007$ . Color pale greenish blue; in section bluish green, not pleochroic. Produced by weathering of hydrothermal minerals, especially fuchsite, as in Serbia and near Ely, Nevada.

**Lembergite**  $^{32} [Na_4Al_4(OH)_4Si_4O_{10}]$  is said to be closely related to kaolinite. It is orthorhombic with  $110 \wedge 010 = 112^\circ$ .  $(+ )2V = 66^\circ 45'$ ,  $r < v$ ,  $N_X = 1.569$ ,

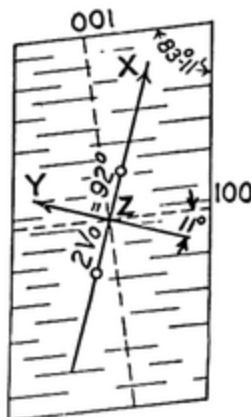


FIG. 249. The optic orientation of dickite.

$^{30}$  J. W. Gruner: *Zeit. Krist.*, LXXXIII, 394 (1932); LXXXV, 345 (1933). A. Brammall, J. G. C. Leech, and F. A. Bannister: *Mineral. Mag.*, XXIV, 507 (1937). S. B. Hendricks: *Am. Mineral.*, XXIII, 295 (1938).

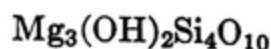
$^{31}$  K. S. Nikogosyan: *Min. Abst.*, VII, 103 (1938).

$^{32}$  A. E. Lagorio: *Trav. Soc. Nat. Varsovie*, VI, Livr. XI, 7 (1895).

$N_Y = 1.570$ ,  $N_Z = 1.573$ ,  $N_Z - N_X = 0.004$ . The optic sign changes to negative when the mineral is heated to  $115^\circ$  (with loss of water). Produced artificially and said to occur in nature. Called nepheline hydrate.<sup>33</sup>

**TALC**

## MONOCLINIC PRISMATIC



$$a:b:c = 0.577:1:2.068 \quad \beta = 100^\circ 15'$$

COMP. Talc often contains a little FeO,  $\text{Al}_2\text{O}_3$ , and rarely even NiO.

STRUC. Space group <sup>28</sup>  $C2/c$ ;  $a$  5.27,  $b$  9.13,  $c$  18.88 Å. U.C. 4.

PHYS. CHAR. Compact foliated masses; perfect 001 cleavage with flexible and somewhat elastic laminae. Percussion figure as in micas, but with lines normal to 010, 110, and  $1\bar{1}0$ . Twinning rare, producing pseudocubic forms.  $H. = 1$ .  $G. = 2.82$ . Insoluble.  $F. = 6$ , after whitening due to exfoliation. Half the water is lost below red heat; the rest between  $875^\circ$  and  $960^\circ$ .

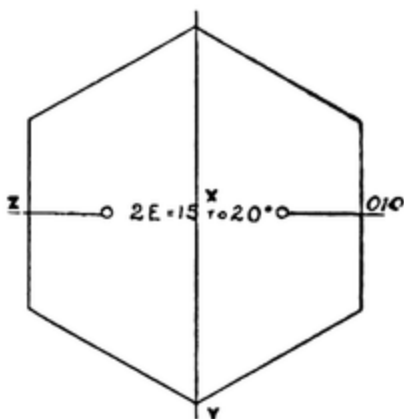


FIG. 250. The optic orientation of talc.

OPT. PROP. The optic plane is 100; X (nearly) normal to 001 cleavage. See Fig. 250. The optic angle is small and may seem to be  $0^\circ$ , owing to superposition of laminae of varying orientation.  $(- )2V = 0^\circ$  to  $30^\circ$ ,  $r > v$ ;  $N_X = 1.538$ – $1.545$ ,  $N_Y = ?$ ,  $N_Z = 1.575$ – $1.590$ ,  $N_Z - N_X = 0.030$ – $0.050$ .

A variety with Ni (*pimelite*) has: <sup>34</sup>  $(- )2V = 30^\circ$ – $80^\circ$ ,  $N_Z' = 1.592$ – $1.615$ ,  $N_Z - N_X = 0.014$ – $0.018$ .

After losing half its water content the mineral has nearly the same optic properties.

Color pale green, white, greenish gray to dark green, reddish by alteration; colorless in thin section.

A mineral <sup>35</sup> with 30.6 NiO (perhaps a nickelian talc) is green with micaceous cleavage.  $G. = 3.037$ .  $(- )2V = 14^\circ \pm 2^\circ$ ,  $N_X = 1.605$ ,  $N_Y \approx N_Z = 1.650$ ,  $N_Z - N_X = 0.045$ . Color green with pearly luster.

OCCUR. Talc is most abundant in certain schists, where it may form rock masses (known as *soapstone* or *steatite*) with minor amounts of other minerals such as tremolite, chlorite, magnetite, etc. Also known in some serpentine, chlorite schist, dolomite, etc. It is an unusual alteration product of olivine, enstatite, etc., in igneous rocks.

DIAG. It differs from pyrophyllite and muscovite in its small optic angle; from brucite in its sign and biaxial character as well as its insolu-

<sup>33</sup> M. Dominikiewicz: *Min. Abst.*, V, 255 (1933).

<sup>34</sup> K. Spangenberg: *Naturw.*, XXVI, 578 (1938).

<sup>35</sup> F. C. Partridge: *Trans. Geol. Soc. S. Africa*, XLVI, 119 (1943).



bility; it is not readily distinguished from sericite, but the indices of refraction may be a little lower.

**Minnesotaite** <sup>36</sup>  $[Fe_3(OH)_2Si_4O_{10}]$  contains some  $Fe'''$ , Mg, and more OH than shown in the formula, but it seems to be essentially an iron analogue of talc. Probably  $a$  5.4,  $b$  9.4,  $c$  19.1 ( $\sin \beta$ ) Å. U.C. 4. Crystals flakes or needles.  $H. = 2.5$ .  $G. = 3.0-3.1(?)$ .  $X$  normal to basal cleavage.  $(- )2V = \text{small}$ ,  $N_X = 1.580$ ,  $N_Z = 1.615$ ,  $N_Z - N_X = 0.035$ . Again: <sup>37</sup>  $N_Z = 1.623$ ,  $N_Z - N_X = 0.040-0.045$ . Colorless or pleochroic with  $X = \text{colorless or very pale yellow}$ ,  $Y = Z = \text{pale green}$ . Found in iron-ore deposits in Minnesota.

### MICA GROUP

The mica group includes silicates of aluminum <sup>38</sup> and potassium (or, rarely, sodium) with hydroxyl or fluorine, and usually with magnesium, iron, or lithium. The members of the group are usually monoclinic and pseudohexagonal, but may be hexagonal or triclinic.<sup>39</sup> All micas have very perfect basal cleavage, giving thin elastic laminae; they are characterized by weak birefringence in cleavage flakes and basal sections combined with strong birefringence in transverse sections.

**PHYS. CHAR.** Crystals of all the micas, when developed under the most favorable conditions for free growth as in pegmatites, are pseudohexagonal prismatic with distinct vertical elongation; but such conditions are rare, and the usual crystals are thin basal plates of hexagonal outline; in all of them the prism angles ( $110 \wedge \bar{1}\bar{1}0$  and also  $110 \wedge 010$ ) are very near  $60^\circ$  and  $120^\circ$ . A blow with a dull point on a cleavage plate of any mica develops a six-rayed "percussion figure," one line being more distinct than the other two (see Fig. 251). This line is parallel to 010 whereas the others are parallel to the prism faces. The percussion figure makes it possible to determine the position of 010 (and hence the optic orientation) in any cleavage piece of mica, even though no crystal faces are present. Pressure instead of a blow on the cleavage surface (001) of mica produces a six-rayed "pressure figure" whose lines are perpendicular to those of the percussion figure.

Twinning is common in mica, the twinning plane being 110 and the composition face 001 or 110. Ferromagnesian micas (biotites) are attacked by acids, leaving a skeleton of silica; other micas are nearly or quite insoluble.  $H. = 2.5-4$ .  $G. = 2.75-3.2$ .  $F. = 2-6$ .

**OPT. PROP.** The negative acute bisectrix ( $X$ ) is nearly normal to the basal cleavage so that cleavage flakes give a nearly centered bisectrix

<sup>36</sup> J. W. Gruner: *Am. Mineral.*, XXIX, 363 (1944).

<sup>37</sup> S. Richarz: *Jour. Geol.*, XXXV, 690 (1927).

<sup>38</sup> By exception taeniolite contains no essential aluminum.

<sup>39</sup> S. B. Hendricks and M. E. Jefferson: *Am. Mineral.*, XXIV, 729 (1939).

interference figure. The optic angle is very small to  $0^\circ$  in biotite and not very large ( $45^\circ$  ca.) in muscovite. The optic plane is normal to 010 in muscovite and parallel thereto in biotite. See Figs. 252 and 253. The refringence is low in lepidolite and phlogopite and distinct in other micas; the birefringence is strong in all micas. Absorption is very strong in colored micas with maximum parallel with the cleavage. The color varies from gray to yellow, brown, green, black, pink, and violet in different types.

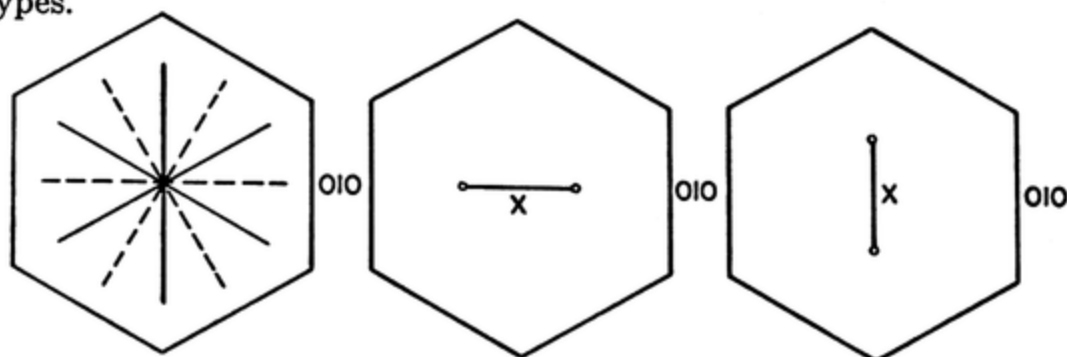


FIG. 251. Percussion figure (in full lines) and pressure figure (in dotted lines) in mica.

FIG. 252. The optic orientation of the heptaphyllite micas (except ferrophenigite).

FIG. 253. The optic orientation of biotite.

DIAG. In thin section micas are characterized by distinct relief (except lepidolite and phlogopite), strong birefringence, acute bisectrix of small optic angle normal to the single perfect cleavage which is marked by fine parallel lines, sensibly (or nearly) parallel extinction, a mottled appearance between crossed nicols, and in colored micas strong absorption parallel to the cleavage.

CLASS. The author's revised classification <sup>40</sup> of the micas follows:

#### I. Heptaphyllite

A. Muscovite	Muscovite proper	$\text{KAl}_2(\text{OH})_2\text{Si}_3\text{AlO}_{10}$
	Ferrimuscovite	$\text{KAlFe}'''\text{(OH)}_2\text{Si}_3\text{AlO}_{10}$
	Picrophenigite	$\text{K}_2\text{MgAl}_3(\text{OH})_4\text{Si}_7\text{AlO}_{20}$
	Ferrophenigite	$\text{K}_2\text{Fe}''\text{Al}_3(\text{OH})_4\text{Si}_7\text{AlO}_{20}$
B. Paragonite		$\text{NaAl}_2(\text{OH})_2\text{Si}_3\text{AlO}_{10}$

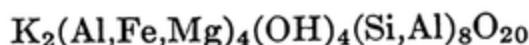
#### II. Octophyllite

C. Lepidolite	Polyolithionite	$\text{K}_2\text{Li}_4\text{Al}_2(\text{OH},\text{F})_4\text{Si}_8\text{O}_{20}$
	Paucilithionite	$\text{K}_2\text{Li}_3\text{Al}_3(\text{OH},\text{F})_4\text{Si}_6\text{Al}_2\text{O}_{20}$
	Protolithionite	$\text{K}_2\text{LiFe}_4\text{Al}(\text{OH},\text{F})_4\text{Si}_6\text{Al}_2\text{O}_{20}$
D. Taeniolite		$\text{KLiMg}_2\text{F}_2\text{Si}_4\text{O}_{10}$
E. Biotite	Phlogopite	$\text{K}_2\text{Mg}_6(\text{OH})_4\text{Si}_6\text{Al}_2\text{O}_{20}$
	Eastonite	$\text{K}_2\text{Mg}_5\text{Al}(\text{OH})_4\text{Si}_5\text{Al}_3\text{O}_{20}$
	Siderophyllite	$\text{K}_2\text{Fe}_5\text{Al}(\text{OH})_4\text{Si}_5\text{Al}_3\text{O}_{20}$
	Annite	$\text{K}_2\text{Fe}_6(\text{OH})_4\text{Si}_6\text{Al}_2\text{O}_{20}$

<sup>40</sup> A. N. Winchell: *Am. Jour. Sci.*, CCIX, 309, 415 (1925); *Am. Mineral.*, XXVII, 114 (1942).

The heptaphyllite micas are characterized chemically by having seven (or fourteen) atoms in the formula (excluding O, H, and F) and optically by having an optic angle (2V) usually of 30° to 50° with the optic plane normal to 010 and dispersion  $r > v$ , except in ferrophengite and roscoelite. The octophyllite micas are characterized chemically by having eight (or sixteen) atoms in their formulas (excluding O, H, and F); biotite is characterized optically by a very small optic angle, and, usually, strong absorption.

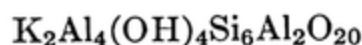
# MUSCOVITE



## MONOCLINIC PRISMATIC

$$a:b:c = 0.574:1:2.217 \quad \beta = 95^\circ 30'$$

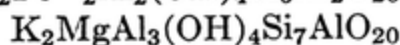
**Muscovite proper**



**Ferrimuscovite**



**Picrophengite**



**Ferrophengite**



**COMP.** Muscovite usually contains some Na replacing K, and may contain Cr or V replacing some Al, as well as F replacing OH; in very rare cases Ba may proxy for some K.

**STRUC.** Space group <sup>41</sup>  $C2/c$ ;  $a$  5.18,  $b$  9.02,  $c$  20.04 Å. U.C. 4.

**PHYS. CHAR.** Crystals usually tabular with hexagonal outline; commonly lamellar massive. Perfect 001 cleavage yielding thin elastic laminae; also secondary parting or slip planes parallel to 110 and 010.  $H. = 2.5-3$ .  $G. = 2.76-3.0$ .  $F. = 5.7$  to gray or yellow glass. Insoluble in acids.

**OPT. PROP.** The optic plane and Z are normal to 010; the negative acute bisectrix X makes an angle of 0° to 2° with a normal to 001. The optic angle (2V) is about 45° for iron-free muscovite; the dispersion is distinct with  $r > v$ . The relief is distinct (with lowered condenser and inclined illumination), and the birefringence is very strong. As shown in Fig. 254 the mean index (and birefringence?) increases rapidly with increase of ferric iron while the optic angle decreases steadily with increase of Mg (and, more rapidly, with increase of ferrous iron).

Data for muscovite and extrapolated properties for ferrimuscovite, picrophengite, and ferrophengite are:

	Muscovite	Ferrimuscovite	Picrophengite	Ferrophengite
(-)2V	47°	38°	25° ca.	15° ca.
Optic plane	⊥010	⊥010	⊥010	010
$N_X$	1.552			
$N_Y$	1.582	1.66 ca.	1.59 ca.	1.61 ca.
$N_Z$	1.588			
$N_Z - N_X$	0.036	0.06 ca.	0.04 ca.	0.04 ca.

<sup>41</sup> W. W. Jackson and J. West: *Zeit. Krist.*, LXXVI, 211 (1931); LXXXV, 160 (1933).

Colorless, gray, brown, pale green, etc. Luster vitreous to pearly. Streak colorless. In thin section colorless, except in some pleochroic halos, which are found only in types containing an appreciable tenor of iron. Such types are pleochroic in thick sections and in halos with  $X < Y = Z$ , and  $X$  = colorless,  $Y = Z$  = pale yellow to brown.

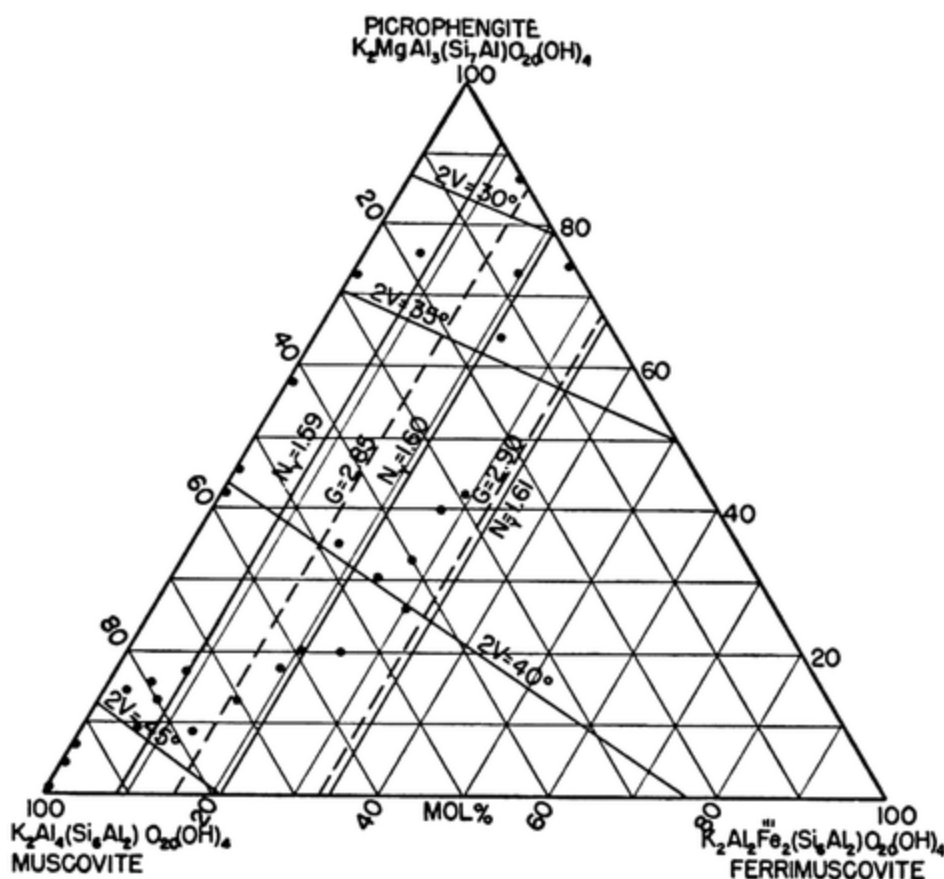


FIG. 254. Properties of muscovite.

*Alurgite* (a manganian phengite) has  $X = Z$  = purplish red,  $Y$  = brownish red.

**INCL.** Zircon crystals are sometimes found as inclusions; they may produce pleochroic halos in otherwise colorless muscovite. Other minerals sometimes present include apatite, spinel, garnet, tourmaline, quartz, and magnetite or hematite, the last in dendritic forms.

**ALTER.** By hydration muscovite alters to *damourite* or "hydromica"; by leaching, which removes the potash, it may alter to kaolinite or gibbsite with quartz, or antigorite or talc with gibbsite.

Nearly colorless muscovite with  $2E = 65^\circ 20'$ ,  $X$  sensibly normal to 001 and the optic plane normal to 010 may be changed<sup>42</sup> by heating about 3 hours at  $1000^\circ$  in air, to an orange color, distinctly pleochroic,

<sup>42</sup> F. Rinne: *Ber. Sächs. Akad. Wiss. Leipzig*, LXXVI, B, 261 (1924); *Zeits. Krist.*, LXI, 113 (1925).

with  $2E = 0^\circ$  ca. and no visible change in the position of X, Y, and Z. A second heating at about  $1000^\circ$  in hydrogen restores the original condition.

**OCCUR.** Muscovite is the most common of the micas. It is a normal constituent of many igneous rocks, especially granites. It is an important constituent of gneiss, mica schist, and related rocks. It occurs in large crystals in veins and pegmatites. It is a secondary mineral frequently, being derived from feldspar, nephelite, scapolite, spodumene, cordierite, kyanite, topaz, etc. It occurs sparingly in sedimentary rocks like shales, but anamorphism of such materials frequently causes its development.

**DIAG.** Muscovite differs from pale phlogopite in the position of the optic plane, from talc in its larger optic angle (in most cases), and from kaolinite, chlorite, etc., in its strong birefringence. It differs from lepidolite in having higher indices of refraction for equal values of the optic angle, as shown in the tabulated data on pages 367 and 371.

*Damourite* is an altered muscovite containing more water or more easily removed water. The cleavage laminae are flexible but lose their elasticity as the change progresses; also the optic angle decreases nearly to zero.

*Sericite* is a fine scaly or fibrous kind of muscovite; the name is usually confined to white mica which is secondary. It is often the result of the alteration of feldspar. Shannon<sup>43</sup> suggests that it contains less potash and more water (therefore sometimes called *hydromuscovite*) and has a smaller optic angle than ordinary muscovite.

*Gümbelilite*<sup>44</sup> seems to be a variety containing considerable picrophengite; it has  $(- )2V = 42^\circ$ ,  $N_X = 1.568$ ,  $N_Y = 1.571$ ,  $N_Z = 1.596$ ,  $N_Z - N_X = 0.028$ .

*Fuchsite* is a chromian muscovite (Cr proxies for part of the Al).  $(- )2E = 54^\circ-70^\circ$ ,  $r > v$  distinct,  $N_X^{45} = 1.559-1.572$ ,  $N_Y = 1.595-1.604$ ,  $N_Z = 1.595-1.612$ ,  $N_Z - N_X = 0.036-0.043$ . Nearly colorless in thin section, but in thick section X = colorless to pale greenish blue, Y = yellowish green, Z = dark bluish green. Found in micaceous quartzites and mica schists, and sparingly in some gneisses and dolomites. *Mariposite*<sup>46</sup> seems to be a chromian phengite.

*Chromochre* is similar, but has more  $Cr_2O_3$  and a very small optic angle; it may be a chromian phengite.

*Roscoelite* is a vanadian muscovite. A sample from the Stockslager mine is about 55 per cent phengite<sup>46</sup> and has  $Al:V = 59:41$ . A sample from the same place<sup>47</sup> has perfect 001 and distinct 010 cleavages with  $H. = 2.5$ ,  $G. = 2.97$ ; optic plane normal to 010, and X nearly normal to 001,  $(- )2E = 42^\circ-80^\circ$  Na,  $r < v$  distinct,  $2V = 35^\circ$  ca.,  $N_X = 1.610-1.615$ ,  $N_Y = 1.682-1.685$ ,  $N_Z = 1.692-1.704$ ,  $N_Z - N_X = 0.077-0.094$ . A sample with 17.4  $V_2O_5$  has<sup>48</sup>  $N_X = 1.59$ ,  $N_Y = 1.63$ ,  $N_Z = 1.64$ ,

<sup>43</sup> E. V. Shannon: *U. S. Nat. Mus. Bull.* 131, 367 (1926).

<sup>44</sup> E. Aruja: *Mineral. Mag.*, XXVII, 11 (1944).

<sup>45</sup> E. Szadeczky-Kardoss: *Min. Abst.*, VII, 105 (1938); C. O. Hutton: *Min. Abst.*, VIII, 340 (1943); Whitmore, Berry, and Hawley: *Am. Mineral.*, XXXI, 1 (1946).

<sup>46</sup> W. F. Hillebrand, H. W. Turner, and F. W. Clarke: *Am. Jour. Sci.*, VII, 451 (1899).

<sup>47</sup> F. E. Wright: *Am. Jour. Sci.*, XXXVII, 305 (1914).

<sup>48</sup> R. C. Wells and W. W. Brannock: *U. S. Geol. Surv. Bull.* 950, 121 (1946).

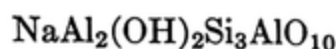


$N_Z - N_X = 0.05$ . Color clove brown to olive green with  $X = Y =$  olive green,  $Z =$  green-brown, and  $X < Y < Z$  (Wright <sup>47</sup>).  $X =$  light greenish yellow,  $Y = Z =$  clove brown to greenish yellow brown (Turner <sup>46</sup>). Abnormal apple-green interference colors on cleavage pieces are characteristic. Roscoelite is associated with gold ores in California and Colorado. Very rare.

Muscovite has another crystal phase (II) <sup>49</sup> which is monoclinic with  $a:b:c = 0.577:1:3.326$ ,  $\beta = 90^\circ \pm 10'$ . Space group  $C2$ ;  $a$  5.20,  $b$  9.03,  $c$  30.04 Å. Three layers instead of two. It occurs in wedge-shaped aggregates with much twinning. Perfect 001 cleavage.  $G = 2.82$ . Muscovite II has the optic plane parallel with 010 and  $Z$  (nearly)  $= a$ .  $(- )2V = 15^\circ$  (by twinning the angle is decreased, varying down to  $3^\circ$ ).  $N_X = 1.555$ ,  $N_Y = 1.589$ ,  $N_Z = 1.590$ ,  $N_Z - N_X = 0.035$ . Color of mass white, but in section pleochroic with  $X =$  pale yellow (greenish),  $Y = Z =$  deeper yellow with more green. Found in Sultan Basin, Washington.

## PARAGONITE

MONOCLINIC



$$a:b:c = 0.571:1:2.112 \quad \beta = ?$$

COMP. Paragonite contains K in place of some Na, and muscovite contains Na in place of some K, but no continuous series is now known. <sup>50</sup>

STRUC. <sup>51</sup>  $a$  5.12,  $b$  8.87,  $c$  sin  $\beta$  18.95 Å. Again: <sup>52</sup>  $b$  8.90,  $c$  19.33 Å.

PHYS. CHAR. Lamellar, usually massive.  $H = 2+$ .  $G = 2.85$ .  $F = 6$ . Insoluble.

OPT. PROP.  $X$  nearly normal to 001;  $Z = b$ .  $(- )2V = 40^\circ$  ca.,  $N_X$  <sup>50</sup>  $= 1.564$ – $1.577$ ,  $N_Y = 1.599$ – $1.605$ ,  $N_Z = 1.600$ – $1.609$ ,  $N_Z - N_X = 0.028$ – $0.038$ . Colorless.

OCCUR. Found with quartz, kyanite, or tourmaline. Very rare.

DIAG. Paragonite cannot be distinguished from muscovite by optical tests alone. Careful tests for tenor of Na and K are needed.

*Brammallite* <sup>51</sup> seems to be a variety of paragonite; it contains 5.22%  $\text{Na}_2\text{O}$  and only 2.58  $\text{K}_2\text{O}$  and has  $(- )2V =$  large,  $N_X = 1.561$ ,  $N_Y = ?$ ,  $N_Z = 1.579$ ,  $N_Z - N_X = 0.018$ . Colorless. Found at Llandebie, South Wales.

## LEPIDOLITE

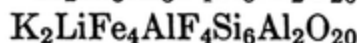
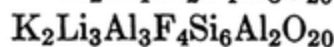
MONOCLINIC DOMATIC <sup>53</sup>

$$a:b:c = 0.58:1:1.12 \quad \beta = 100^\circ$$

Polyolithionite

Paucilithionite

Protolithionite



<sup>49</sup> J. M. Axelrod and F. S. Grimaldi: *Am. Mineral.*, XXXIV, 559 (1949).

<sup>50</sup> W. T. Schaller and R. E. Stevens: *Am. Mineral.*, XXVI, 541 (1941); G. Koch: *Chem. Erde*, IX, 453 (1935).

<sup>51</sup> F. A. Bannister: *Mineral. Mag.*, XXVI, 304, 307 (1943).

<sup>52</sup> J. W. Gruner: *Am. Mineral.*, XXVII, 131 (1942).

<sup>53</sup> Also, sometimes trigonal trapezohedral— $C3_112$ , with  $a$  5.3,  $c$  30.0 Å (S. B. Hendricks and M. E. Jefferson: *Am. Mineral.*, XXIV, 729, 1939); sometimes triclinic pinacoidal.



**COMP.** Nearly all analyses of lepidolite show a deficiency of  $Li_2O$ ; the author<sup>54</sup> considers that this is due to the presence of some inter-layered (but not isomorphously combined) muscovite. *Zinnwaldite* contains considerable protolithionite (with the other end-members); *cryophyllite* is similar.

**STRUC.** Space group<sup>39</sup>  $Cm$ ;  $a$  5.3,  $b$  9.2,  $c$  10.2 Å. U.C. 1. Lepidolite may also be trigonal trapezohedral or triclinic, depending upon variations in the stacking of successive layers.

**PHYS. CHAR.** Crystals usually short prismatic or lamellar, often in aggregates. Perfect 001 cleavage; twinning on 110 rather uncommon.

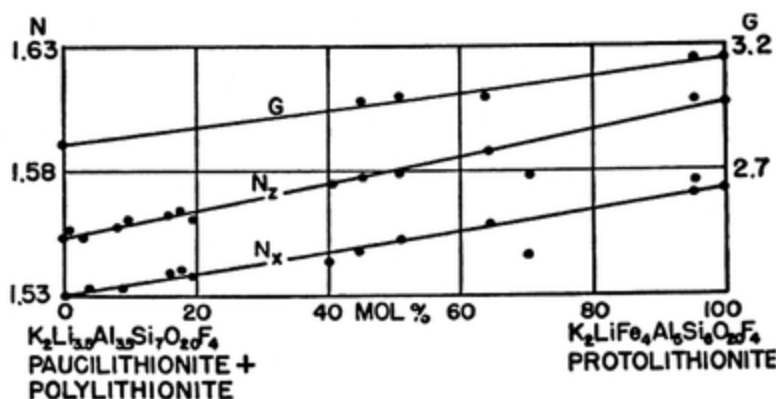


FIG. 255. Properties of the lepidolite series.

H. = 2.5–4. G. = 2.8–3.3. F. = 1.5–2.5. More or less attacked by acids.

**OPT. PROP.** The optic plane is parallel to 010 and  $X \wedge c = 0^\circ$  ca. in most lepidolite including zinnwaldite (monoclinic); it is normal to 010 and  $X \wedge c = 6^\circ$ – $7^\circ$  in (triclinic?) lepidolite. The optic angle varies from  $25^\circ$  to  $50^\circ$ , except in the hexagonal phase ( $0^\circ$ ) and protolithionite (near  $0^\circ$ ). The relief is low to moderate, and the birefringence moderate to strong. The optic properties of (muscovite-free) lepidolite vary with the composition about as follows<sup>55</sup> (as deduced chiefly from Figs. 255 and 256):

Polyolithionite	Paucilithionite	Zinnwaldite	Protolithionite
(-)2V = $45^\circ$ ca.	$25^\circ$ ca.(?)	$30^\circ$ ca.	$0^\circ$ ca.
$N_X = 1.543$ ca.	$1.535$ ca.	$1.55$ ca.	$1.57$ ca.
$N_Y = 1.555$ ca.	$1.554$ ca.	$1.58$ ca.	$1.61$ ca.
$N_Z = 1.558$ ca.	$1.555$ ca.	$1.58$ ca.	$1.61$ ca.
$N_Z - N_X = 0.015$ ca.	$0.020$ ca.	$0.03$ ca.	$0.035$ ca.

<sup>54</sup> A. N. Winchell: *Am. Mineral.*, XXVII, 114 (1942).

<sup>55</sup> These data are inaccurate for two reasons: 1. Lepidolite has at least three crystal phases, and they have not been studied separately. 2. Interlayered muscovite is believed to be common, and its effects can only be estimated. For zinnwaldite J. J. Glass (*Am. Mineral.*, XX, 741, 1935) gives: (-)2V =  $0^\circ$ – $33^\circ$ ,  $N_X = 1.550$ – $1.558$ ,  $N_Y = 1.580$ – $1.589$ ,  $N_Z = 1.580$ – $1.590$ .

The color of lepidolite is pink, red, violet, yellow, gray, white; zinnwaldite is violet, yellow, gray, brown; protolithionite is brown, greenish,

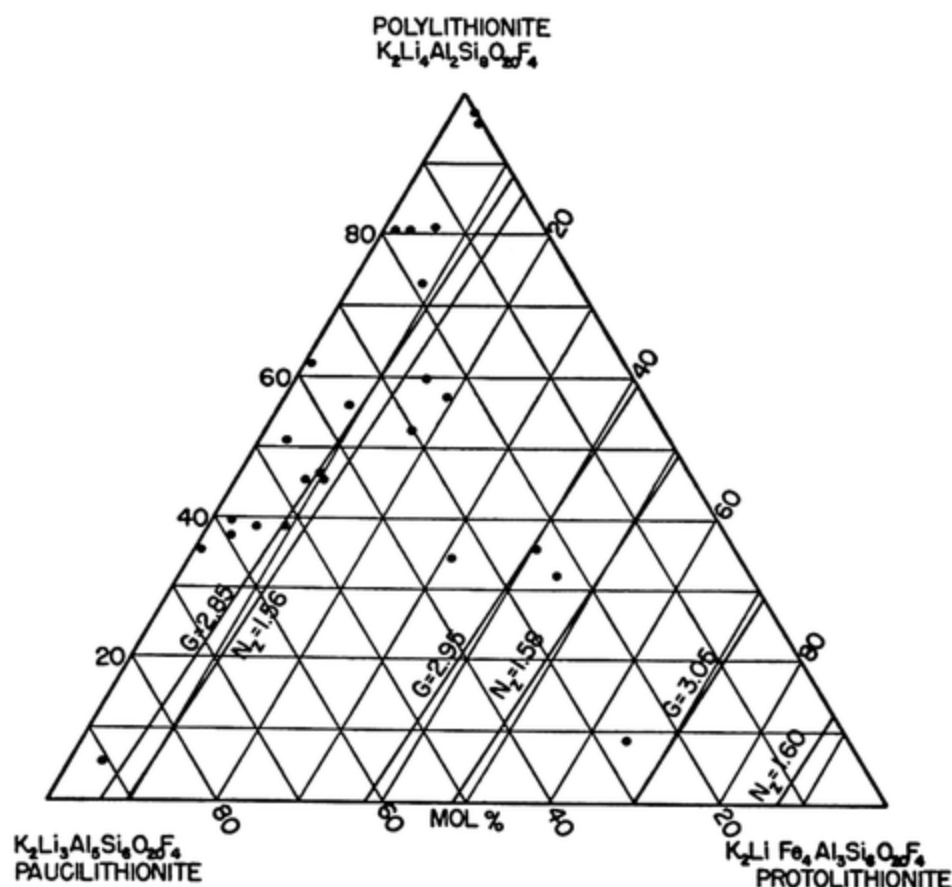


FIG. 256. Properties of the lepidolite system (without muscovite).

black; the lighter-colored types are colorless in thin section; others are pleochroic, as follows:

Paucilithionite			
Polyolithionite	Zinnwaldite	Cryophyllite	Proto-
X = Colorless	Yellowish, reddish	Green	lithionite
Y = Pink, violet	Brownish gray, brown	Brownish red	Brown
Z = Pink, violet	Brownish gray, brown	Brownish red	Brown

**INCL.** Rutile, zircon, cassiterite, and topaz are known as inclusions, usually surrounded by pleochroic halos.

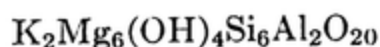
**OCCUR.** Lepidolite is found in veins and pegmatites with cassiterite, topaz, tourmaline, etc. It is commonly in parallel growths with muscovite.

**DIAG.** It differs from biotite in the position of the optic plane in some specimens; it usually has a delicate color rather than the dark green or brown of biotite; it has lower refringence than muscovite of the same optic angle.

*Taeniolite*<sup>56</sup> ( $KLiMg_2Si_4O_{10}F_2$ ) is monoclinic like muscovite with perfect basal cleavage.  $H. = 2.5-3$ .  $G. = 2.83-2.86$ . Fusible.  $(- )2V = \text{near } 0^\circ$ ,  $N_X = 1.522$ ,  $N_Y = N_Z = 1.553$ ,  $N_Z - N_X = 0.031$ . Colorless. Found in veins with quartz, dickite, rutile, etc., as at Narsarsuk, Greenland, and Magnet Cove, Arkansas.

**BIOTITE** MONOCLINIC DOMATIC  $K_2(OH)_4(Mg,Fe,Al)_6(Si,Al)_8O_{20}$   
 $a:b:c = 0.576:1:1.109$   $\beta = 100^\circ$

**Phlogopite**



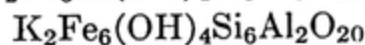
**Eastonite**



**Siderophyllite**



**Annite**



**COMP.** Besides the variations shown in the formulas OH may be replaced by F, K in part by Na, Al in part by  $Fe'''$  or Ti,  $Fe''$  in part by Mn, etc. Biotite rich in iron is called *lepidomelane*.

**STRUC.** Space group<sup>39</sup>  $Cm$ ;  $a$  5.3,  $b$  9.2,  $c$  10.2 Å. U.C. 2. Biotite has four other different crystal phases! One is monoclinic prismatic—space group  $C2/c$ ,  $a$  5.3,  $b$  9.2,  $c$  20.2; another is trigonal trapezohedral—space group  $C3_12$ ,  $a$  5.3,  $c$  30.0 Å (and so uniaxial); two others are triclinic—space group  $P\bar{1}$ —6 layer with  $a$  5.3,  $b$  5.3,  $c$  60.0 Å or 24 layer with  $a$  5.3,  $b$  5.3,  $c$  240.0 Å,  $\alpha = 90^\circ \text{ ca.}$ ,  $\beta = 90^\circ \text{ ca.}$ ,  $\gamma = 120^\circ \text{ ca.}$

**PHYS. CHAR.** Crystals are monoclinic, but almost hexagonal; usually six-sided prisms; often massive lamellar. Perfect basal cleavage; also 010 and 111 parting, thus giving the percussion and pressure figures. Twinning on 110 in thin 001 laminae.  $H. = 2.5-3$ .  $G. = 2.8-3.4$ .  $F. = 5$ . Decomposed by  $H_2SO_4$  leaving scales of silica. May be bent or broken in rocks that have been under strain.

**OPT. PROP.** The plane of the optic axes is parallel<sup>57</sup> to 010 and the acute bisectrix  $X$  is sensibly normal to 001. The relief is low (phlogopite) to high and the birefringence strong (phlogopite) to extreme (annite). The optic angle is practically zero in most biotite, but may reach  $70^\circ$  for  $2E$  in rare cases. The dispersion is weak with  $r < v$ . The optic

<sup>56</sup> H. D. Miser and R. E. Stevens: *Am. Mineral.*, XXIII, 104 (1938).

<sup>57</sup> M. E. Jefferson reports a few exceptions to this rule (*Am. Mineral.*, XXIV, 729, 1939).

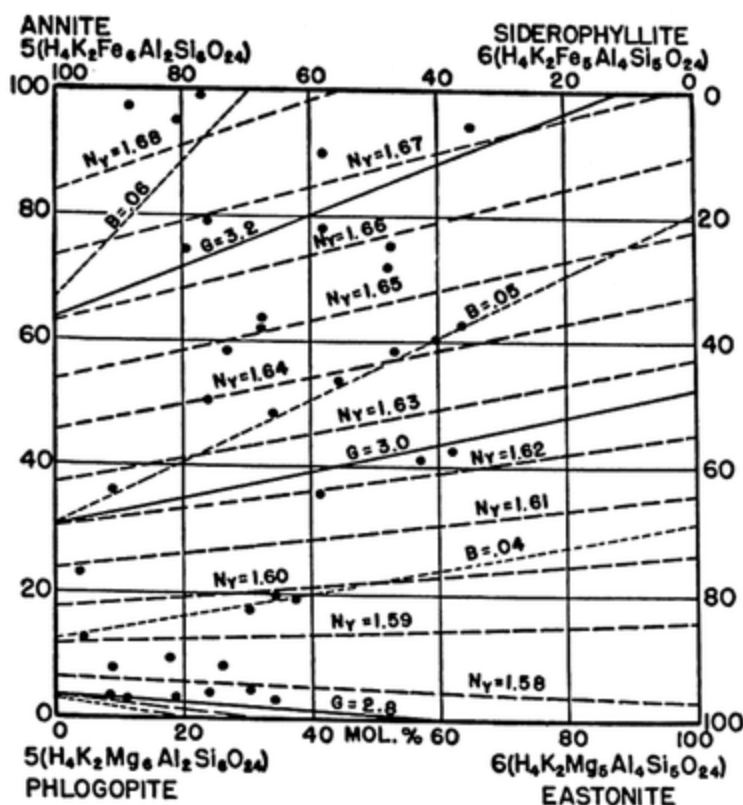


FIG. 257. Properties of biotite. Each dot represents an analysis.

properties vary with the composition as follows (as deduced chiefly from Fig. 257):

	Phlogopite <sup>58</sup>	Eastonite	Siderophyllite	Annite
(-) $2V = 10^\circ$ ca.		Small	Small	Small
$N_X = 1.535$		1.542	1.616	1.630
$N_Y = 1.564$		1.577	1.670	1.690
$N_Z = 1.565$		1.578	1.670	1.690
$N_Z - N_X = 0.030$		0.036	0.054	0.060
$G = 2.75$		2.86	3.19	3.35

Ordinary biotite has  $2V = 0^\circ$  or very near  $0^\circ$ ,  $N_X = 1.56-1.60$ ,  $N_Y = N_Z = 1.60-1.66$ ,  $N_Z - N_X = 0.040-0.060$ . In rare types of biotite (probably containing  $Fe_2O_3$  and/or  $TiO_2$ )  $N_Z$  may reach 1.73;<sup>59</sup>

<sup>58</sup> Artificial phlogopite with all the OH replaced by F has  $(- )2V = 0^\circ$ ,  $N_X = 1.520$ ,  $N_Y = N_Z = 1.558$ ,  $N_Z - N_X = 0.038$  (D. P. Grigoriev: *Cent. Min.*, 1934A, 219). Artificial fluorbiotite with  $Fe:Mg = 1:2$  and formula:  $K(Fe,Mg)_3F_2Si_3AlO_{10}$  has  $(- )2V = 0^\circ$ ,  $N_X = 1.551$ ,  $N_Y = N_Z = 1.596$ ,  $N_Z - N_X = 0.045$  (D. P. Grigoriev: *Min. Abst.*, VII, 284, 1939). A white phlogopite with  $N_Z$  as high as 1.582 has been found by P. V. Kalinin: *Chem. Abst.*, XLI, 5060 (1947).

<sup>59</sup> C. S. Ross in F. C. Edson: *Okla. Geol. Surv. Bull.* 31, 15 (1925).

again, a biotite<sup>60</sup> with 16.48  $Fe_2O_3$  and 24.36  $FeO$  has  $2V = 21^\circ$  ca.,  $N_X = 1.616$ ,  $N_Y = ?$ ,  $N_Z = 1.697$ ,  $N_Z - N_X = 0.081$ .

Siderophyllite<sup>61</sup> with 1.01  $MnO$ , 1.01  $Li_2O$ , and 30.16  $FeO$  has  $G. = 3.12$ ,  $(-)2V = 6^\circ-8^\circ$ ,  $N_X = 1.590$ ,  $N_Z = 1.641$ .

A very rare type of biotite<sup>62</sup> found at Långban, Sweden, seems to be a ferric iron equivalent of phlogopite, with some manganese; it has  $(-)2E = 22^\circ 20'$ ,  $2V = 13^\circ 40'$ ,  $r > v$  strong,  $N_X = 1.622$ ,  $N_Y = 1.636$ ,  $N_Z = 1.636$ ,  $N_Z - N_X = 0.014$ ,  $X =$  light red,  $Z =$  dark red.

A biotite<sup>63</sup> with 3.14  $Cs_2O$  has  $G. = 3.10$ ,  $N_X = 1.573$ ,  $N_Y = N_Z = 1.620$ ,  $N_Z - N_X = 0.047$ .

Color of the phlogopite-eastonite series is yellowish brown, reddish, greenish, yellow, colorless; usually pleochroic even in thin section with  $X =$  colorless,  $Y = Z =$  brownish yellow, and  $X < Y < Z$ . The color becomes darker with increase of iron, and the annite-siderophyllite series is black, green, brown, or red; even with much less iron the color is very dark so that most biotite is deeply colored with marked pleochroism as follows:

$X =$ Colorless	Pure yellow	Pure yellow	Pale to dark yellow
$Y =$ Reddish brown	Reddish brown	Dark brown to opaque	Grass green to opaque
$Z =$ Golden yellow	Reddish brown	Dark brown to opaque	Grass green to opaque

Absorption usually  $X < Y < Z$ , but it may be  $X < Z < Y$ . The ray vibrating parallel to the cleavage is always absorbed more than the ray vibrating normal thereto.

INCL. Acicular inclusions are common in phlogopite; they cause asterism on account of their arrangement along lines crossing at about  $60^\circ$ . They are rutile, hematite, tourmaline, or an unknown mineral of low relief and strong birefringence. Pleochroic halos are more abundant about inclusions in biotite than in any other mineral. These inclusions may be zircon, apatite, or titanite, less commonly allanite, rutile, or liquids. The pleochroism in the halos is similar in color and position to that of the biotite, but it is more intense so that the halo is often opaque parallel to  $Y$  and  $Z$ . The refringence and birefringence are greater in the halo than in other parts of the biotite. If the mica be heated to a high temperature without fusion the halos may disappear.

<sup>60</sup> G. Schauburger: *Cent. Min.*, 1927A, 103.

<sup>61</sup> R. R. Coats and J. J. Fahey: *Am. Mineral.*, XXIX, 373 (1944).

<sup>62</sup> J. Jakob: *Zeit. Krist.*, LXI, 155 (1924). A rare mica with 8.30  $Mn_2O_3$  is said to have  $X =$  dark brown and  $Z =$  light brown; also  $(-)2V = 33^\circ 30'$ ,  $N_X = 1.573$ ,  $N_Y = 1.610$ ,  $N_Z = 1.613$ ,  $N_Z - N_X = 0.040$ .

<sup>63</sup> F. L. Hess and J. J. Fahey: *Am. Mineral.*, XVII, 173 (1932).

ALTER. Biotite alters readily (probably under hydrothermal conditions) to chlorite, either directly, or by first changing from brown to green, and then going to chlorite. The green mineral is considered still a mica since the birefringence is very strong, about as in the brown original. Epidote, calcite, quartz, rutile, anatase, or brookite may be produced by alteration of biotite in place of or with chlorite.

Weathering of biotite usually changes it by loss of alkalies to a brown or golden yellow mineral with bronze luster. This substance has soft, flexible, inelastic laminae; heated to 100° it loses water, and at a higher temperature it exfoliates and opens out into wormlike forms (hence the name *vermiculite*). It has strong birefringence like micas and unlike chlorites; the chemical composition is not well known but seems to be variable.

Under the influence of high temperature, biotite may suffer notable changes. The exterior may change without loss of form to magnetite, with or without augite, or it may recrystallize in part to biotite. Or it may change to hematite, to magnetite, spinel, and hypersthene, with occasional sillimanite and recrystallized biotite. Heating biotite to 1000° produces the following changes: <sup>64</sup>

Temp. °C.	2E (obs.)	N <sub>Z</sub> (obs.)	FeO	Ignition Loss
20	0° ca.	1.641	10.32	2.76
400	0° ca.	1.643		
600	15.7°	1.655		
800	31.5°	1.689		
1000	38.4°	1.711	5.96	1.53

Mehmel <sup>65</sup> has shown that dilute sulfuric acid leaches and bleaches biotite leaving little more than silica; also that heating to 700° (which must cause oxidation) changes the index (N<sub>Z</sub>) from 1.65 to 1.82.

OCCUR. Phlogopite is rare in igneous rocks, but not so uncommon in exomorphosed dolomites. Siderophyllite and annite are found in pegmatite. Biotite is an important constituent of many igneous rocks and of some metamorphic rocks such as gneiss and schist, where it may replace or accompany muscovite. It is a product of both regional and contact metamorphism. It is not rare in sediments, though it may change to chlorite during katamorphism. *Lepidomelane* is any kind of biotite rich in iron; *meroxene* has been used as a name of "normal biotite," that is, biotite with the optic plane parallel to 010; it might be better to apply it to normal biotites with magnesia dominant over iron oxide.

<sup>64</sup> S. Kozu and B. Yoshiki: *Sci. Rep. Tōhoku Univ. Sendai*, III, 177 (1929).

<sup>65</sup> M. Mehmel: *Chem. Erde*, XI, 307 (1937).



**DIAG.** Biotite differs from heptaphyllite chemically and also in the (usual) position of the optic plane, the very small optic angle, and the dispersion; biotite is usually dark-colored and pleochroic, while heptaphyllite is usually light-colored or colorless, but these differences are not constant.

**Anomite** is a rare variety of biotite having the optic plane normal to 010. The cause of this condition is not yet known.<sup>68</sup>

**GLAUCONITE** MONOCLINIC  $\left\{ \begin{array}{l} K(Mg,Fe)(Al,Fe)(OH)_2Si_4O_{10} + \\ K(Al,Fe)Al(OH)_2Si_3AlO_{10} \end{array} \right.$   
 $a:b:c = 0.577:1:2.208$   $\beta = 95^\circ 0'$

**COMP.** Six end-member formulas are suggested in the formulas given above, but it is known that these are not accurate,<sup>67</sup> partly because K is commonly insufficient. *Skolite*<sup>68</sup> is an aluminous glauconite. *Celadonite* is a ferric glauconite.

**STRUC.** Much like mica.<sup>69</sup>  $a$  5.24,  $b$  9.07,  $c$  20.03 Å.

**PHYS. CHAR.** Usually in granules, rarely as large as 0.1 mm., long supposed to be amorphous, but actually composed of fine laminae with distinct 001 and 101(?) cleavages.  $H. = 2$ .  $G. = 2.5-2.86$ .  $F. = \text{easy}$ . *Skolite* is attacked by acid, leaving a skeleton of hydrated silica which is biaxial and negative.

**OPT. PROP.** The acute bisectrix  $X$  is nearly normal to the 001 cleavage.  $(- )2V = 0^\circ-20^\circ \pm$ ,  $r > v$ . The range of variation of the indices, as derived from Fig. 258,

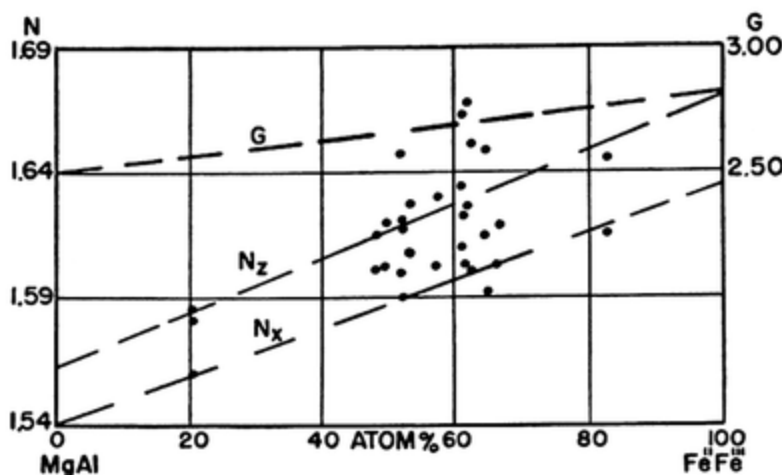


FIG. 258. Properties of glauconite.

<sup>66</sup> S. Kozu and B. Yoshiki (*Sci. Rep. Tōhoku Univ. Sendai*, III, 177, 1929) state that ordinary biotite changes to anomite when heated. But F. Rinne (*Ber. Akad. Wiss. Leipzig*, LXXVI, B, 261, 1924) found no such change; when dark green biotite was heated for 3 hours at 1000° it became dark brown with  $X = \text{red-brown}$ ,  $Y = \text{yellowish brown}$ ,  $Z = \text{dark red-brown}$ , and the optic angle changed from about 0 to  $2E = 65^\circ$  or even  $82^\circ Na$ .

<sup>67</sup> See S. B. Hendricks and C. S. Ross: *Am. Mineral.*, XXVI, 683 (1941). Also C. O. Hutton and F. T. Seelye: *Am. Mineral.*, XXVI, 595 (1941).

<sup>68</sup> K. Smulikowski: *Am. Mineral.*, XXIII, 541 (1938). *Bravaisite* as defined by Smulikowski and J. de Lapparent (*Min. Abst.*, VII, 100, 1938) seems to be closely related to skolite. It has  $(- )2V = 5^\circ$ ,  $N_z = 1.588-1.598$ ,  $N_z - N_x = 0.032$ ; again  $(- )2V = 8^\circ$ ,  $N_x = 1.544$ ,  $N_z = 1.574$ ,  $N_z - N_x = 0.030$ .

<sup>69</sup> J. W. Gruner: *Am. Mineral.*, XX, 699 (1935).

is:  $N_X = 1.545-1.63$ ,  $N_Y$  nearly  $= N_Z$ ,  $N_Z = 1.57-1.66$ ,  $N_Z - N_X = 0.025-0.03$ . For skolecite  $N_X = 1.559$ ,  $N_Y = 1.581$ ,  $N_Z = 1.586$ ,  $N_Z - N_X = 0.030$ . For celadonite  $N_X = 1.608$  ca.,  $N_Z = 1.638$  ca.

Color olive green, blackish green; by alteration, yellowish to brownish. In thin section green with X = straw yellow to pale yellowish green, Y and Z = clear green to yellowish green, and  $X < Y$  and  $Z$ .

**OCCUR.** Glauconite is found in marine sediments, associated with detrital minerals such as feldspar and quartz; usually also with animal remains. It is now being formed on ocean bottoms at depths of 600 to 5000 feet. It is also an alteration product (called *celadonite*) of igneous and sedimentary rocks.

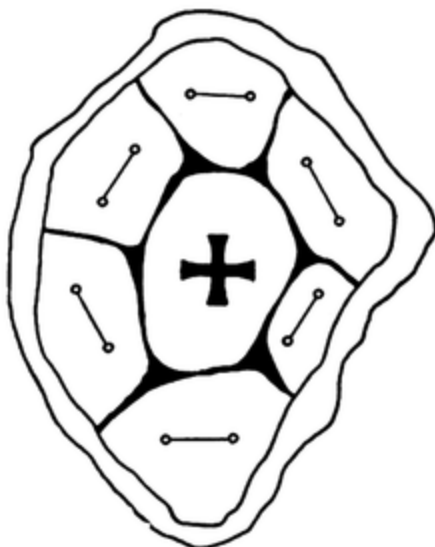


FIG. 259. Uniaxial and biaxial cookeite. Material from Paris, Maine.

**DIAG.** The microcrystalline texture of the grains and the color are rather characteristic.

**Cookeite**  $[\text{LiAl}_4(\text{OH})_8\text{Si}_3\text{AlO}_{10}]$  is monoclinic<sup>70</sup> with  $a:b:c = 0.574:1:3.169$ ,  $a$  5.13,  $b$  8.93,  $c$  sin  $\beta$  28.30 Å. U.C. 4. Perfect 001 cleavage; laminae flexible, but not elastic.  $H. = 2.5$ .  $G. = 2.69$ .  $F. = 6$  with exfoliation. Attacked by  $\text{H}_2\text{SO}_4$ . Axis Z normal<sup>71</sup> to 001.  $(+)2V = 0^\circ-80^\circ$ ,  $N_X = 1.576$ ,  $N_Y = 1.579$ ,  $N_Z = 1.597$ ,  $N_Z - N_X = 0.021$ . Again:<sup>68</sup>  $N_X = 1.565$ ,  $N_Y = 1.580$ ,  $N_Z = 1.595$ ,  $N_Z - N_X = 0.030$ . A cleavage plate may be divided into six biaxial sectors around a uniaxial center,<sup>72</sup> as in Fig. 259. A narrow border with  $N = 1.54$  may surround all grains. Color white, yellowish green, pink; colorless in section. Found with tourmaline, apparently as an alteration product. Found at Varutrask, Sweden; Ogofau, Wales; Paris, Maine; etc.

<sup>70</sup> A. Brammell, J. G. C. Leech, and F. A. Bannister: *Mineral. Mag.*, XXIV, 507 (1937).

<sup>71</sup> R. W. Goranson in K. K. Landes: *Am. Mineral.*, X, 390 (1925).

<sup>72</sup> Figure supplied by H. Winchell, personal communication, April 9, 1938.

**CHRYSOTILE**<sup>73</sup>

## MONOCLINIC PRISMATIC



$$a:b:c = 1.583:1:0.577 \quad \beta = 93^\circ 16'$$

**COMP.** Chrysotile may contain a little FeO, Mn, or  $Al_2O_3$ ; in *garnierite* Ni proxies for Mg.

**STRUC.** Space group probably  $C2/m$ ;  $a$  14.66,  $b$  9.24,  $c$  5.33 Å. U.C. 4.

**PHYS. CHAR.** Usually fibrous; the fibers are separable and flexible in the variety called *asbestos*. Poor 110 cleavages at  $130^\circ$ .  $H. = 2-3$ .  $G. = 2.36-2.5$ .  $F. = 6$ . Decomposed to fibrous silica by HCl.

**OPT. PROP.** The optic plane is 010 and  $Z$  nearly  $= c$ , that is, the elongation. The optic angle is small and may appear to be zero on account of superposition of lamellae of varying orientation. See Fig. 260.  $(+)2V = 30-35^\circ$ ,  $N_X = 1.542$  (Larsen<sup>74</sup>),  $N_Y = 1.543$  calc.,  $N_Z = 1.555$ ,  $N_Z - N_X = 0.013$ .

Chrysotile<sup>75</sup> with 2.57 NiO has a mean index,  $N = 1.558$ ; a sample with 7.68 NiO and 0.14 ZnO has<sup>76</sup>  $N_X = 1.561$ ,  $N_Y = 1.567$ ,  $N_Z = 1.568$ ,  $N_Z - N_X = 0.007$ ; another with 4.31 FeO has<sup>77</sup>  $N = 1.565$ .

Color green, yellow, gray. In thin section, pale greenish or yellow to colorless; in thicker sections, distinctly pleochroic with  $X = Y =$  greenish yellow to colorless,  $Z =$  green or yellow.

**OCCUR.** Chrysotile is commonly associated with antigorite in the rock known as serpentine; also found in veins in such rocks; less commonly an alteration product of ferromagnesian minerals in other rocks.

**DIAG.** It differs from antigorite in its optic sign, small optic angle, and somewhat stronger birefringence, as well as by its fibrous rather than lamellar structure. It differs from fibrous amphiboles by its much weaker birefringence, lower relief, and parallel extinction.

**Deweylite** is perhaps a chrysotile with surplus water. It has  $G. = 2.2-2.4$ .  $Z$  parallel to fibers.  $(+)2E =$  small;  $N_Y = 1.505$  to  $1.525$  (with<sup>78</sup> 4.2 NiO).

**Garnierite**<sup>79</sup> is usually considered to be a nickel chrysotile, but it commonly contains excess silica, indicating the probable presence of admixed opal or of another hydrous nickel silicate. Garnierite with little nickel (2-5% NiO) is isotropic, or nearly so, with  $N =$  about 1.57; with much nickel (47% NiO)  $(+)2V = 0^\circ-10^\circ$ ,  $N_X = 1.622$ ,  $N_Z = 1.630$ ,  $N_Z - N_X = 0.008-0.010$ . See Fig. 260a. Color dark green with  $X < Z$ ; rarely yellowish. Garnierite is the chief nickel ore in New

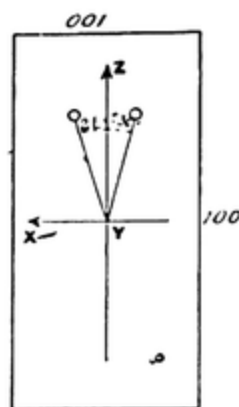


FIG. 260. The optic orientation of chrysotile.

<sup>73</sup> B. E. Warren: *Am. Mineral.*, XXVII, 235 (1942); also *Zeit. Krist.*, LXXVI, 201 (1930), and E. Aruja: *Mineral. Mag.*, XXVII, 65 (1945).

<sup>74</sup> E. S. Larsen (*U. S. Geol. Surv. Bull.* 679, 1921) reports much lower indices and explains the higher values as due to loss of water on heating in making thin sections; he gives  $(+)2V =$  large,  $N_X = 1.508$ ,  $N_Y = 1.512$ ,  $N_Z = 1.522$ ,  $N_Z - N_X = 0.014$ . After heating to make a thin section this crystal had  $N_X = 1.539$ .

<sup>75</sup> C. S. Ross and E. V. Shannon: *Am. Mineral.*, XI, 90 (1926).

<sup>76</sup> E. V. Shannon and E. S. Larsen: *Am. Mineral.*, XI, 28 (1926).

<sup>77</sup> M. Savul: *Min. Abst.*, III, 450 (1927).

<sup>78</sup> C. S. Ross and E. V. Shannon: *Am. Mineral.*, X, 444 (1925).

<sup>79</sup> W. T. Pecora, S. W. Hobbs, and K. J. Murata: *Econ. Geol.*, XLIV, 13 (1949). Also K. Spangenberg. *Zent. Mineral.*, 1938A, 360.

Caledonia, associated with steatite, talc, etc.; also known in Oregon, North Carolina, and elsewhere.

**Nouméite** seems to be an aggregate of garnierite, talc, etc.

**Xylotile** is a ferriferous chrysotile(?) in which the iron is partly oxidized to the ferric state.  $G. = 2.55$  (green type); 2.4 (brown type). Fusible. Decomposed by HCl.  $Z$  parallel to elongation ( $c$ ).  $(+)2E = 20^\circ$  ca.,  $N = 1.57$  ca.,  $N_Z - N_X = 0.026$  ca. Color green or brown, and strongly pleochroic with  $X = Y =$  pale

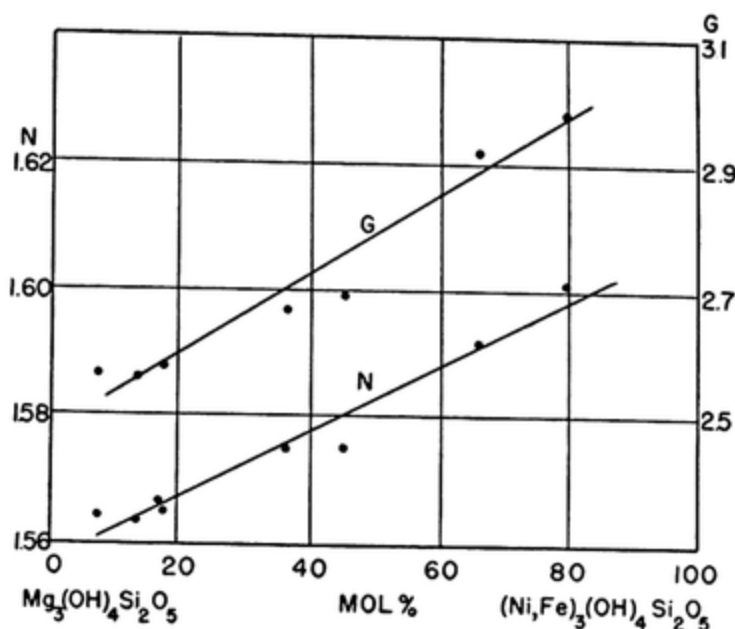


FIG. 260a. Properties of garnierite.

yellowish,  $Z =$  very dark golden yellow. Found in serpentine and crystalline limestone.

**Asbophite**<sup>80</sup> is chemically like chrysotile but has a different X-ray pattern;  $(+)2V = 64^\circ$ ,  $N_X = 1.559$ ,  $N_Y = 1.562$ ,  $N_Z = 1.570$ ,  $N_Z - N_X = 0.011$ .

**Greenalite**<sup>81</sup>  $[Fe''_9Fe'''_2(OH)_{16}Si_8O_{20}]$  is monoclinic and closely related to chrysotile;  $a$  14.5,  $b$  18.6,  $c$ ? Å. U.C. 2(?). Found in granules with no cleavage. Crystallization mostly submicroscopic, but distinct to X-rays.  $G. = 3. \pm$ . Isotropic, or nearly so, with  $N = 1.686$  F, 1.674 D, 1.660 C. Dispersion,  $F - C = 0.016$ .  $N$  also variable to 1.650 (Hawley<sup>82</sup>). Color green, to yellow or brown from alteration. In thin section green, yellow, brown, black. An important constituent of iron ores on the Mesabi Range.

**Ishkyldite** ( $H_{20}Mg_{15}Si_{11}O_{47}$ ?) is biaxial<sup>83</sup> and closely related to chrysotile, but the spacing along the fibers (9.68 Å) is nearly twice as great.  $G. = 2.62$ . Soft. The optic plane and  $X$  are normal to the parting plane;  $Z$  is parallel with the fibers.  $(-)2V = 58^\circ$ ,  $N_X = 1.566$ ,  $N_Y = 1.57$  calc.,  $N_Z = 1.573$ ,  $N_Z - N_X = 0.007$ . Color pale bluish green. Found in serpentine near Ishkyldino, middle Volga.

<sup>80</sup> F. V. Syromyatnikov: *Min. Abst.*, X, 454 (1949).

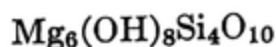
<sup>81</sup> J. W. Gruner: *Am. Mineral.*, XXI, 449 (1936).

<sup>82</sup> J. E. Hawley in A. N. Winchell: *Opt. Mineralogy*, Part II, 413 (1933).

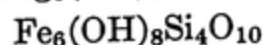
<sup>83</sup> F. V. Syromyatnikov: *Am. Mineral.*, XXI, 48 (1936).

**CHLORITE** <sup>83a</sup> MONOCLINIC PRISMATIC  $(Mg, Fe, Al)_6(OH)_8(Si, Al)_4O_{10}$   
 $a:b:c = 0.57:1:3.08$   $\beta = 97^\circ$  ca.

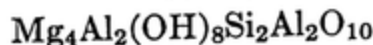
**Antigorite** <sup>84, 85</sup>



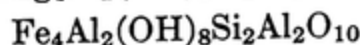
**Ferroantigorite**



**Amesite** <sup>86</sup>



**Daphnite**



COMP. Chlorite is a hydrous silicate of magnesium and iron with or without aluminum. Also, aluminum may be replaced, at least in part, by ferric iron or chromium, and magnesium by nickel or manganese.

CLASS. There are many varieties of chlorite; some of the most important may be defined in terms of the end-members as follows (Ant = antigorite, FeAnt = ferroantigorite, At = amesite, Dn = daphnite):

Names	% (3At + 3Dn)	% (2Ant + 2FeAnt)	% (2FeAnt + 3Dn)	% (2Ant + 3At)
Antigorite	0-20	100-80	0-20	100-80
Jenkinsite	0-20	100-80	20-40	80-60
Penninite	20-40	80-60	0-20	100-80
Delessite	20-40	80-60	20-40	80-60
Clinochlore	40-60	60-40	0-20	100-80
Rumpfite	40-60	60-40	20-40	80-60
Diabantite	40-60	60-40	40-60	60-40
Brunsvigite	40-60	60-40	60-80	20-40
Corundophilite	60-80	40-20	0-20	100-80
Prochlorite	60-80	40-20	20-40	80-60
Ripidolite	60-80	40-20	40-60	60-40
Aphrosiderite	60-80	40-20	60-80	40-20
Thuringite	60-80	40-20	80-100	20-0
Amesite	80-100	20-0	0-20	100-80
Daphnite	80-100	20-0	80-100	20-0

<sup>83a</sup> *Serpentine* is chlorite with no trivalent element.

<sup>84</sup> H. Berman (*Am. Mineral.*, XXII, 342, 1937) questions continuous variation from antigorite to aluminous chlorites. Like Tschermak he also separates "leptochlorites" from other chlorites. The author considers this unnecessary if ferrous iron can be oxidized in chlorite without destroying the crystal.

<sup>85</sup> E. Aruja (*Mineral. Mag.*, XXVII, 65, 1945) gives for antigorite:  $a:b:c = 4.697:1:0.786$ ,  $\beta = 91^\circ 24'$  with  $a$  43.3,  $b$  9.2,  $c$  7.25 Å.

<sup>86</sup> Amesite has a structure unlike that of other chlorites, according to R. C. McMurchy (*Zeit. Krist.*, LXXXVIII, 420, 1934) and A. F. Hallimond (*Mineral. Mag.*, XXV, 441, 1939), and similar to that of kaolinite (J. W. Gruner: *Am. Mineral.*, XXIX, 422, 1944).

For convenience in petrographic work a classification based on optic properties is needed, as follows:

Name	Optic Sign	$N_Y$	$N_Z - N_X$
Antigorite	—	1.55–1.58	0.004–0.010
Jenkinsite	—	1.58–1.61	0.004–0.010
—Penninite	—	1.56–1.59	0.000–0.004
Delessite	—	1.59–1.61	0.000–0.004
Diabantite	—	1.61–1.63	0.000–0.004
Aphrosiderite	—	1.63–1.65	0.000–0.004
Daphnite	—	1.65–1.67	0.000–0.004
Brunsvigite	—	1.63–1.65	0.004–0.010
Thuringite	—	1.65–1.68	0.004–0.010
+Penninite	+	1.57–1.59	0.000–0.004
Rumpfite	+	1.59–1.61	0.000–0.004
Ripidolite	+	1.61–1.63	0.000–0.004
Clinochlore	+	1.57–1.59	0.004–0.010
Prochlorite	+	1.59–1.62	0.004–0.010
Amesite <sup>87</sup>	+	1.58–1.61	0.010–0.025

These two classifications are only roughly equivalent; the relations between them are shown in Fig. 261.

STRUC. Space group  $C2/m$  <sup>88</sup> or  $C2/c$ ; <sup>89</sup>  $a$  5.2–5.4,  $b$  9.2–9.36,  $c$  <sup>90</sup> 28.30–28.58 Å. U.C. 4.

PHYS. CHAR. Lamellar with perfect 001 cleavage; the cleavage flakes are flexible but not elastic. Percussion and pressure figures like those of mica. Twinning on 001 as composition face (penninite law), also on 110 with 001 as composition face (mica law).  $H. = 2-2.5$ .  $G. = 2.6-3.0$ . Easily attacked by acids.

OPT. PROP. The optic plane is parallel to 010, and the acute bisectrix is sensibly normal to 001. The optic orientation of antigorite and of twins of penninite and clinochlore is shown in Figs. 262–266. The refringence varies from low to moderate and the birefringence from imperceptible to moderate, but the latter is decidedly weak in the common types. Dispersion strong. Some chlorites (notably penninite) show abnormal interference colors (e.g., ultra blue) such as are found in only one other common mineral, clinozoisite, which has much higher relief. These colors are probably due to an isotropic state for part of the spectrum, with an anisotropic condition for another part.

<sup>87</sup> J. E. de Villiers: *Trans. Geol. Soc. S. Africa*, XLVIII, 17 (1945).

<sup>88</sup> L. Pauling: *Proc. Nat. Acad. Sci.*, XVI, 578 (1930).

<sup>89</sup> R. C. McMurphy: *Zeit. Krist.*, LXXXVIII, 420 (1934).

<sup>90</sup> W. Engelhardt (*Zeit. Krist.*, CIV, 142, 1942) gives  $c$  14.0–14.1. But E. Aruja (*Mineral. Mag.*, XXVII, 65, 1945) finds an  $a$  axis 8 times as long, or 43.4, and gives  $C2/m$  or  $C2$  or  $Cm$  as the space group.



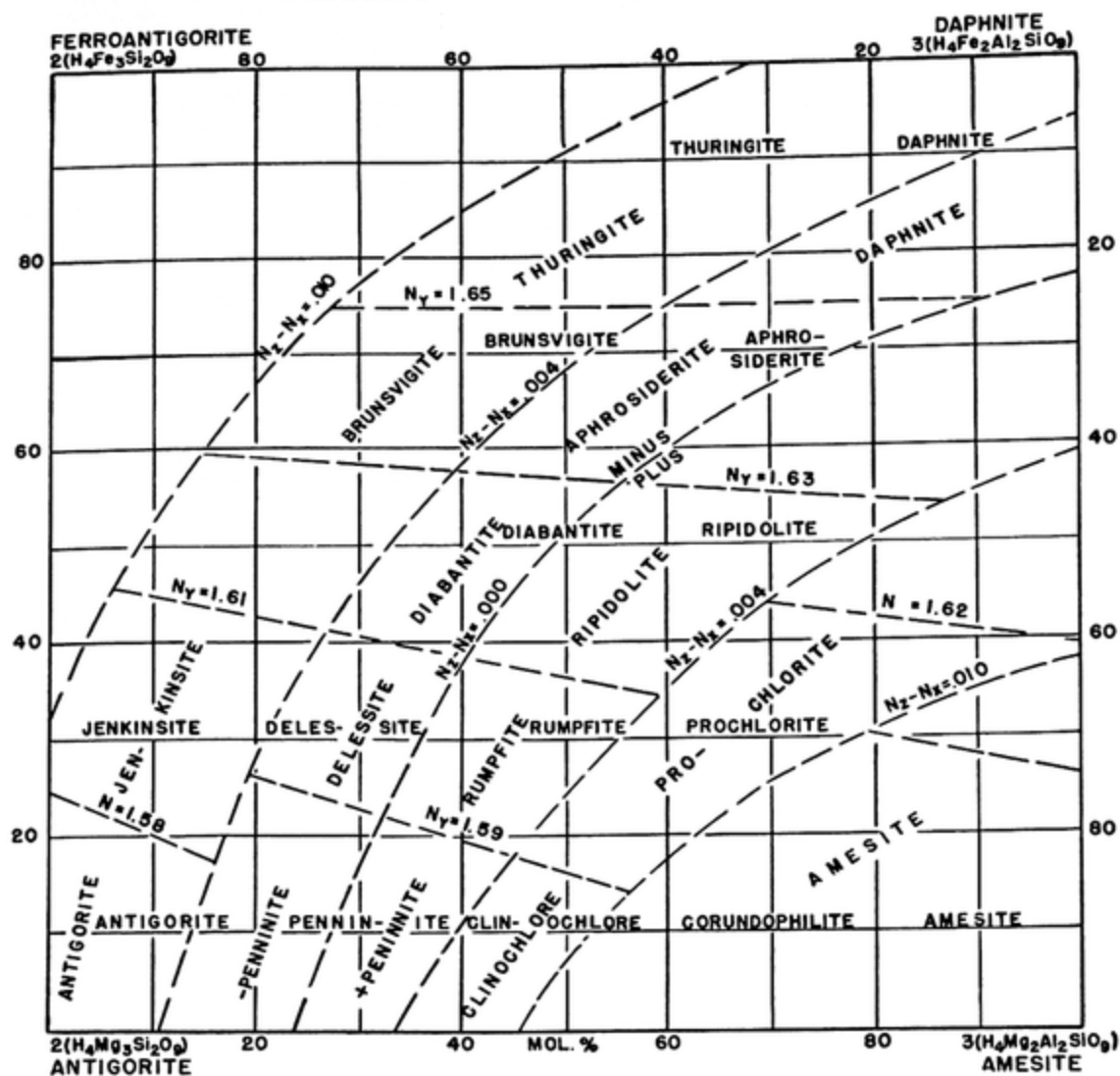


FIG. 261. Chemical and optical classifications of chlorite.

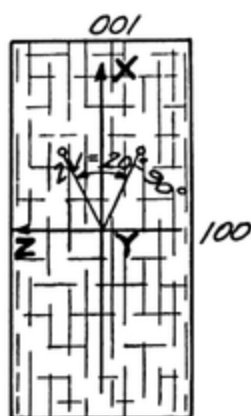
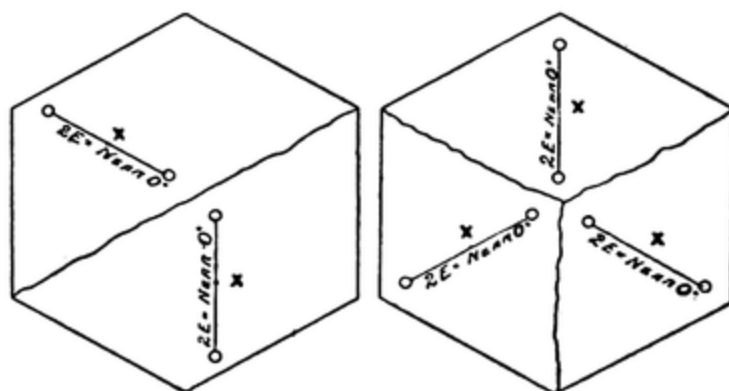
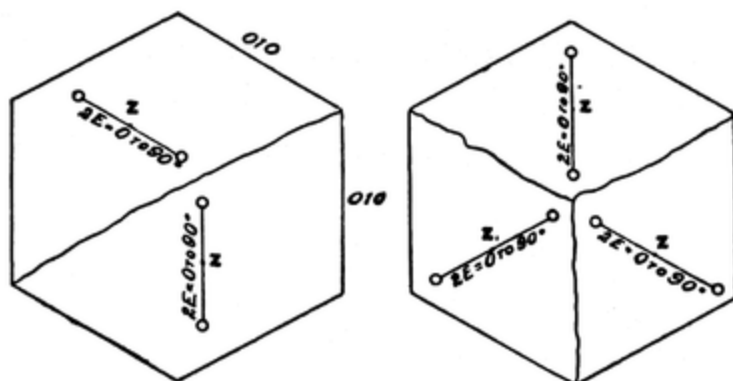


FIG. 262. The optic orientation of antigorite.



FIGS. 263, 264. The optic orientation of penninite twins.



FIGS. 265, 266. The optic orientation of clinoclone twins.

The properties of the various kinds of chlorite are given approximately in the following table.

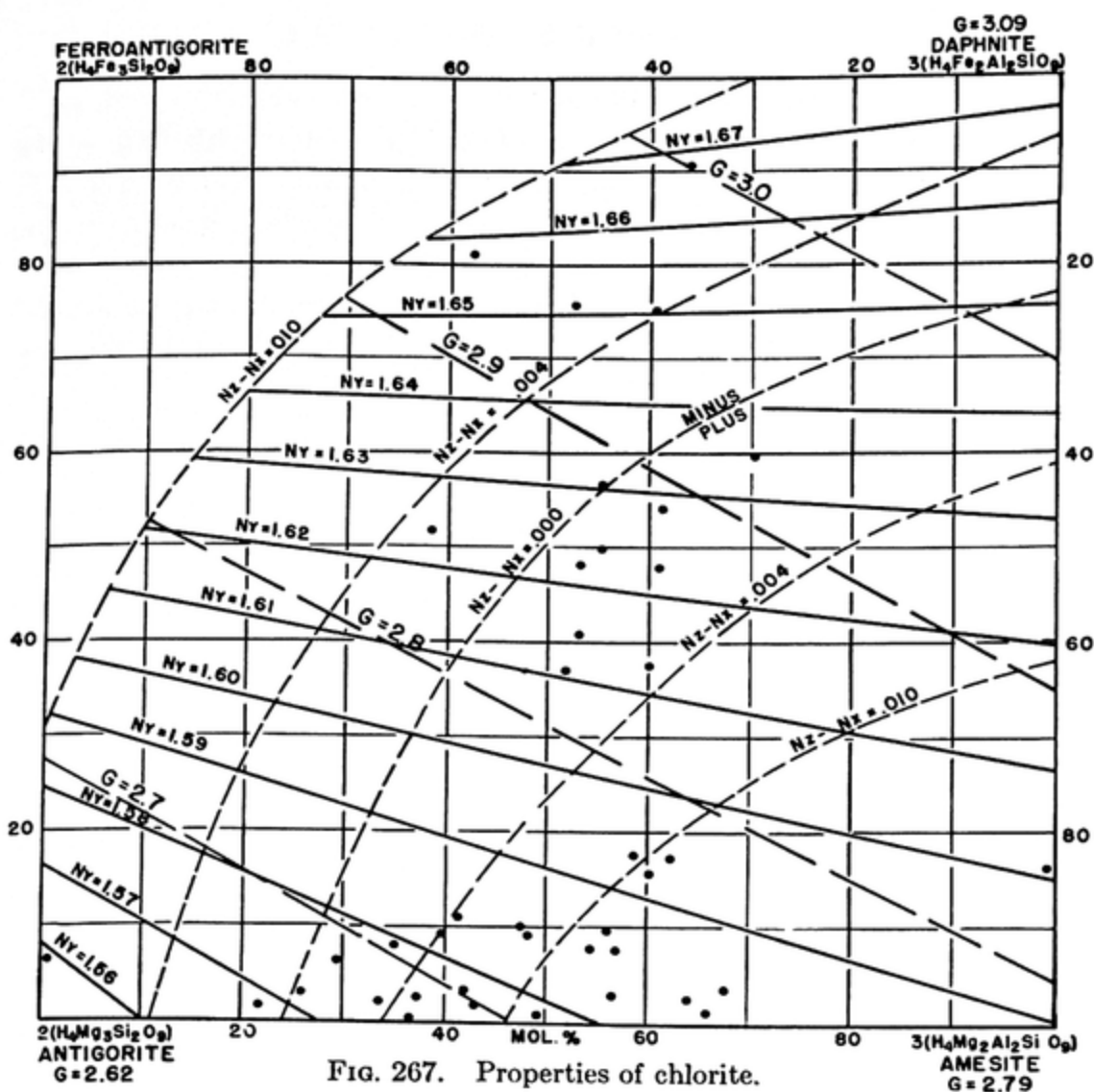
Name	2V	$N_Y$	$N_Z - N_X$	G.	Color
Antigorite <sup>91</sup>	(-)Mod.	1.57	0.007	2.62	Greenish, grayish, yellowish
-Penninite	(-)Small $r > v$	1.57	0.003	2.7	Green, rarely red, violet, white
+Penninite	(+)Small $r < v$	1.58	0.003	2.7	Green; rarely red, violet, white
Clinoclone <sup>92</sup>	(+)0°-40°	1.58	0.007	2.7	Green, olive, pink, white
Corundophilite	(+)30°	1.59	0.012	2.8	Green
Amesite <sup>93</sup>	(+)Small	1.60	0.015	2.79	Bluish green
Jenkinsite	(-)Small	1.59	0.007	2.8	Olive green
Delessite	(-)0°	1.60	0.003	2.8	Green, pink
Rumpfite	(+)0°-10°	1.60	0.003	2.7	Green
Prochlorite	(+)20°	1.60	0.007	2.7	Green; rarely brown or gray
Diabantite	(-)0°	1.62	0.003	2.8	Green, olive
Ripidolite	(+)0°	1.62	0.003	2.8	Green; rarely brown
Brunsvigite	(-)Small	1.64	0.007	2.9	Green
Aphrosiderite	(-)Small	1.64	0.003	3.0	Green
Thuringite	(-)Small	1.66	0.008	3.1	Olive to dark green
Daphnite	(-)Small	1.66	0.003	3.08	Dark green

These properties are shown in part in Fig. 267.

<sup>91</sup> Antigorite with  $H_2O^+$  2.80 and  $H_2O^-$  13.19 has  $N_Y = 1.537$ . See S. Caillère: *C. R. Acad. Sci. Paris*, CXCVI, 628 (1933).

<sup>92</sup> A manganian clinoclone with 0.14 MnO has (+)2V = 0°,  $N_X = 1.588$ ,  $N_Z = 1.594$ , and X = Y = colorless, Z = pale brownish yellow. See C. O. Hutton: *Min. Abst.*, VI, 364 (1936).

<sup>93</sup> An amesite with only 4% Ant (and 1.28%  $Fe_2O_3$ , 0.48% NiO) has  $N_X = N_Y = 1.588$ ,  $N_Z = 1.611$ ,  $N_Z - N_X = 0.023$ . See J. E. de Villiers: *Trans. Geol. Soc. S. Africa*, XLVIII, 17 (1945). Another amesite is reported as negative with 2V = 3-4°,  $N_X = 1.632$ ,  $N_Y$  and  $N_Z = 1.640$ . See D. P. Serdyuchenko: *Min. Abst.*, X, 50 (1949).



Chlorite, as the name implies, is nearly always green, but it can be gray, white, red, brown, yellow. Usually pleochroic; for example:

Name	X	Y	Z
Antigorite —Penninite	Pale greenish yellow Very pale yellow-green	Pale green Green	Pale green Green
†Penninite	Green	Green	Very pale yellow-green
Clinochlore	Pale green	Pale green	Pale yellow-green to colorless
Corundophilite	Deep blue-green	Deep blue-green	Pale brownish green
Delessite	Pale green or yellow	Green or pink	Green or pink
Prochlorite	Green or yellow-green	Green or yellow-green	Colorless, yellow, brownish
Ripidolite	Green or yellow-green	Green or yellow-green	Colorless, yellow, brownish
Aphrosiderite	Colorless or pale	Green	Green
Thuringite	Nearly colorless	Dark green	Dark green
Daphnite	Pale yellowish	Green	Olive green

Other colors are possible in all cases.

*Aerinite* is a ferriferous chlorite of a blue color with  $N_Z - N_X = 0.0115$ ;  $X$  = yellowish or colorless,  $Y = Z$  = dark cobalt blue. It gives off water and turns to a wood-brown color when heated in the closed tube.

*Bastite* is a coarse variety of antigorite which is pseudomorphous after pyroxene, usually enstatite, but sometimes diopside. It forms by slow

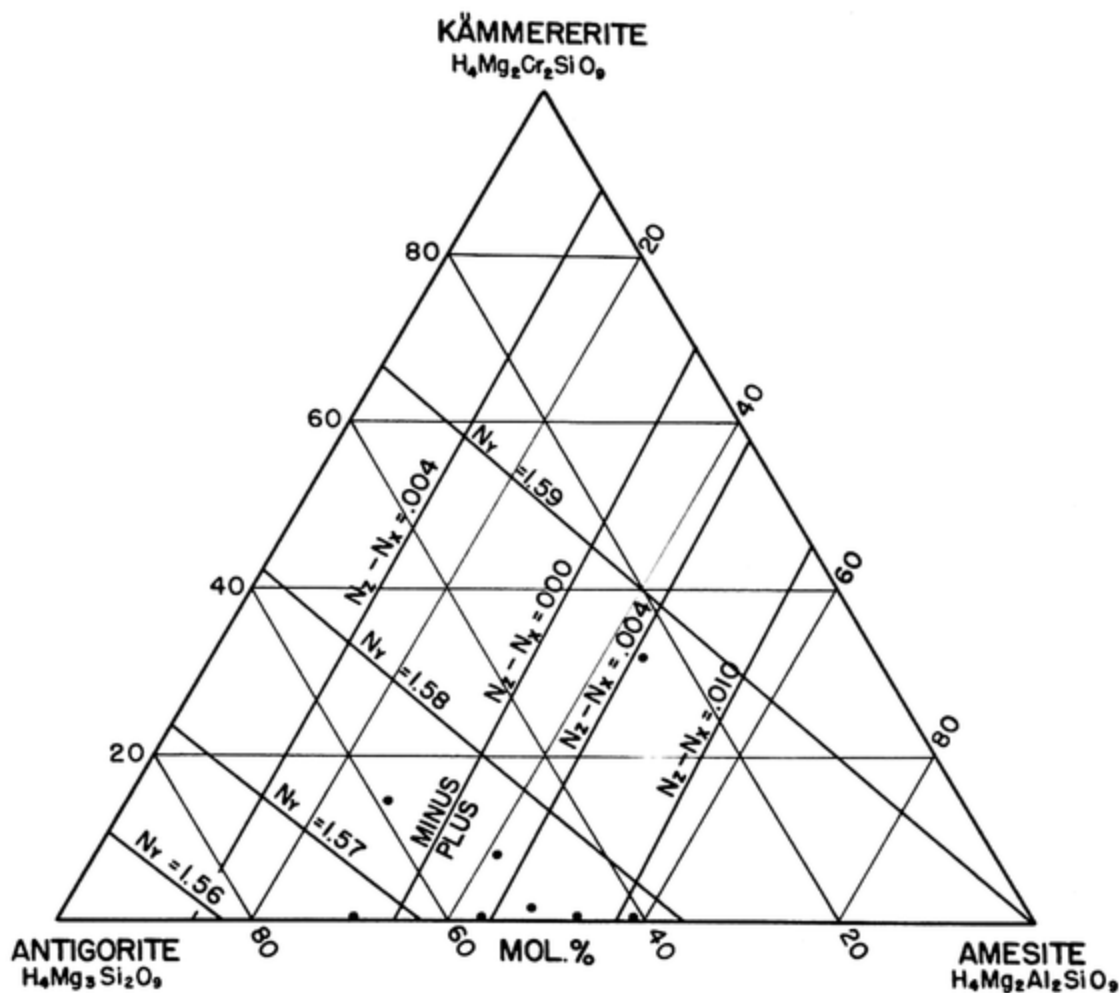


FIG. 268. Properties of the antigorite-amesite-kämmererite system.

growth so that one crystal of pyroxene is replaced by one crystal of bastite in which the perfect 001 cleavage of the bastite is parallel with the 010 parting of pyroxene.

Chromian chlorite is assumed to vary to an end-member containing no aluminum— $Mg_4Cr_2Si_2Cr_2O_{10}(OH)_8$  known as *kämmererite*. Assuming the absence of iron, for simplification, the relations between variations in composition and in optic properties are shown in Fig. 268, which is only an approximation based on scanty data. Chlorite containing any important tenor of chromium is easily recognized by the lavender or

violet color. A sample <sup>94</sup> with only 1.70 Cr<sub>2</sub>O<sub>3</sub> (and 13.20 Al<sub>2</sub>O<sub>3</sub>) has (+)2V = 0° ca., N<sub>X</sub> = 1.576, N<sub>Z</sub> = 1.580, N<sub>Z</sub> - N<sub>X</sub> = 0.004.

Nickelian chlorite varies to an end-member [Ni<sub>6</sub>Si<sub>4</sub>O<sub>10</sub>(OH)<sub>8</sub>] known as *nepouite*.<sup>95</sup> Variations of optic properties with variations of composition are shown approximately in Fig. 269. (-)2V = 0°-12°, N<sub>Z</sub> = 1.57-1.64, N<sub>Z</sub> - N<sub>X</sub> = usually 0.018-0.022 but may reach 0.035. An intermediate type has been called *schuchardite*.<sup>96</sup> Color green with X = pale bluish green to colorless, Z = yellow-green to brownish olive green, or rarely bluish green. The mineral easily absorbs chinolin (if it is contained in immersion liquids used), which leads to a small increase in refractive indices and a change in optic sign from negative to positive. Found at Nepoui, New Caledonia, etc.

INVER. Antigorite and chrysotile seem to be dimorphous, but the mutual relations are unknown.

ALTER. In chlorite with an appreciable tenor of ferrous iron oxidation of the iron seems to occur rather easily. Such chlorite is always fine

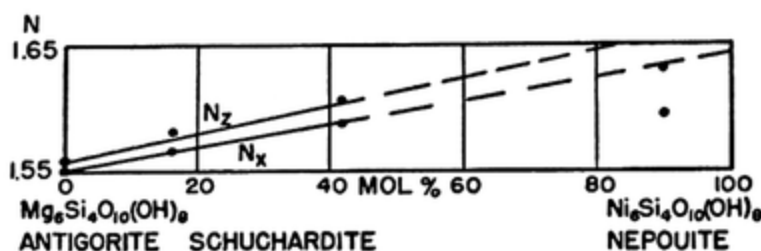


FIG. 269. Properties of the antigorite-nepouite series.

grained; it was named *leptochlorite* by Tschermak; the alteration increases the refringence and also the birefringence; it may change the sign from plus to minus. For example, Shannon <sup>97</sup> reports that a chlorite containing 9.12% Fe<sub>2</sub>O<sub>3</sub> and Fe:Mg = 59:41 has N<sub>Y</sub> = 1.637 and N<sub>Z</sub> - N<sub>X</sub> = 0.023. Orcel <sup>98</sup> reports that chlorite containing 10.56 Fe<sub>2</sub>O<sub>3</sub> and Fe:Mg = 76:24 has N<sub>Y</sub> = 1.665 and N<sub>Z</sub> - N<sub>X</sub> = 0.012; another with 17.95 Fe<sub>2</sub>O<sub>3</sub> and Fe:Mg = 48:52 has N<sub>Y</sub> = 1.685 and N<sub>Z</sub> - N<sub>X</sub> = 0.015. Simpson <sup>99</sup> reports that a chlorite with 9.88 Fe<sub>2</sub>O<sub>3</sub> and Fe:Mg = 89:11 has N<sub>Y</sub> = 1.684 and N<sub>Z</sub> - N<sub>X</sub> = 0.003. Holzner <sup>100</sup> finds that a chlorite with 13.13 Fe<sub>2</sub>O<sub>3</sub> and Fe:Mg = 75:25 has N<sub>Y</sub>

<sup>94</sup> E. Sanero: *Per. Min. Roma*, IV, 473 (1933).

<sup>95</sup> E. Glasser: *C. R. Acad. Sci. Paris*, CXLIII, 1173 (1906); A. Lacroix: *Minéral. France*, IV, 741 (1910).

<sup>96</sup> K. Spangenberg: *Cent. Min.*, 1938A, 360.

<sup>97</sup> E. V. Shannon: *Bull. U. S. Nat. Mus.*, CXXXI, 378 (1926).

<sup>98</sup> J. Orcel: *Bull. Soc. Fr. Min.*, L, 75 (1927).

<sup>99</sup> E. S. Simpson: *Jour. Roy. Soc. W. Australia*, XXIII, 17 (1936-37).

<sup>100</sup> J. Holzner: *N. Jahrb. Min.*, Bl. Bd. A, LXXIII, 389 (1938).

$= 1.651$  and  $N_Z - N_X = 0.005$ . By heating ripidolite to redness Dschang<sup>101</sup> produced the following effects:

	Before Heating	After Heating
FeO	28.07	3.16
Fe <sub>2</sub> O <sub>3</sub>	2.42	30.0
N <sub>X</sub>	1.637	1.674
	Isotropic	Negative

The effects of the oxidation of ferrous iron in certain types of chlorite are shown diagrammatically in Fig. 270. The base line of this figure corresponds with a line from a point on the base of Fig. 267 representing about 57% of  $3(\text{H}_4\text{Mg}_2\text{Al}_2\text{SiO}_9)$  to a point on the top line of the same

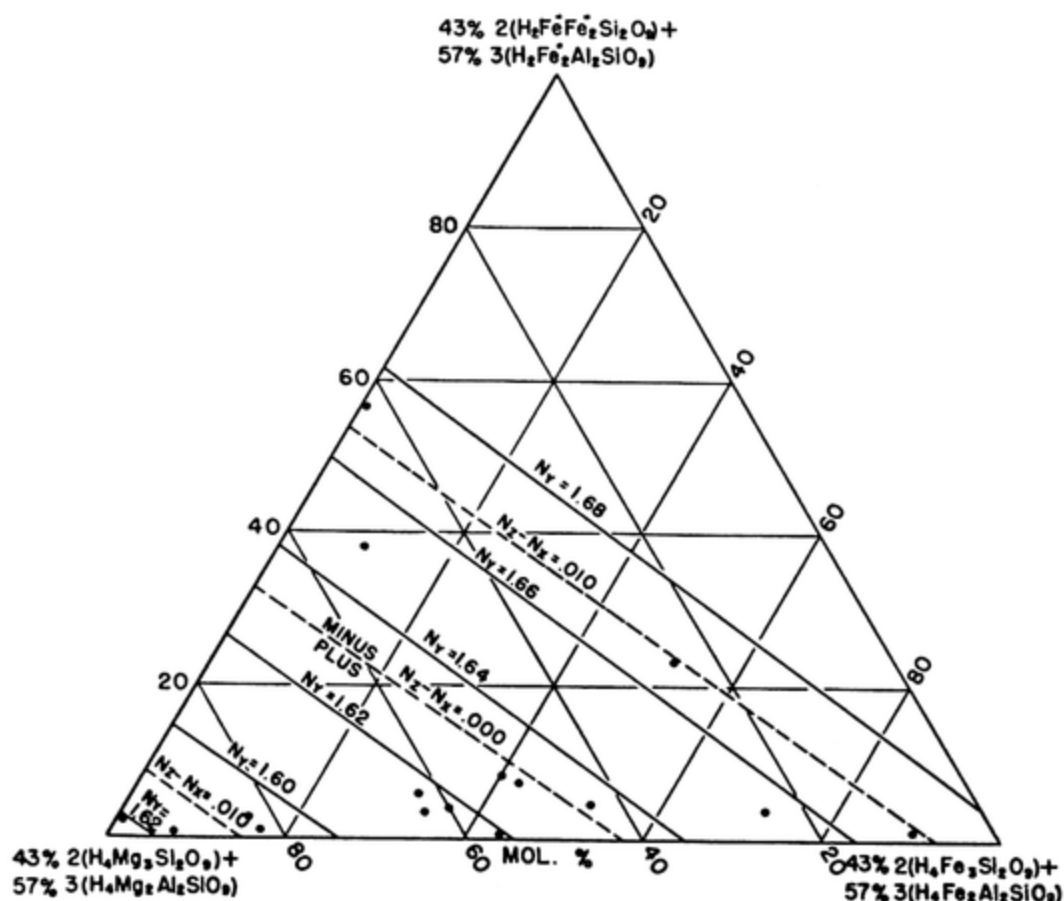


FIG. 270. Effects of oxidation of ferrous iron on the properties of certain chlorites.

figure representing the same percentage of  $3(\text{H}_4\text{Fe}_2\text{Al}_2\text{SiO}_9)$ . The formulas at the lower left corner of the diagram contain no iron and therefore take no part in the oxidation, which may affect the formulas

<sup>101</sup> G. L. Dschang: *Chem. Erde*, VI, 416 (1931).



at the lower right corner from 0 to 100 per cent. Accordingly, Dschang's ripidolite in its original condition belongs near the middle of the base line (at 8); the same mineral after oxidation is near the middle of the upper left line (at 8a); it is evident that it has moved in a direction parallel with the upper right border. The same change has raised the refringence from 1.637 to 1.674 and the birefringence from zero to an unmeasured amount (from the diagram, about 0.011). Diagrams for other percentages of the aluminous molecules would probably be similar.

**OCCUR.** Chlorite is widely distributed in nature, being found in nearly all kinds of rocks, usually as an alteration product of biotite, pyroxene, amphibole, garnet, or olivine. Chlorite is abundant in some anamorphic rocks, notably in chlorite schist.

**DIAG.** Chlorite is characterized by the very common green color, distinct though often weak pleochroism, weak birefringence, and strong dispersion; also by flexible inelastic cleavage flakes and lack of alkalis.

**Pennantite** <sup>102</sup>  $[Mn_4Al_2(OH)_8Si_2Al_2O_{10}]$  is a manganese equivalent of daphnite. It gives the X-ray pattern of thuringite with  $a$  5.43,  $b$  9.4,  $c$  28.5 Å. Found in tiny flakes with  $G. = 3.06$ .  $(- )2V = 0^\circ$  ca.,  $N_X = 1.646$ ,  $N_Y = N_Z = 1.661$ ,  $N_Z - N_X = 0.015$ . Color orange-red with  $X' =$  orange-buff,  $Z'$  (parallel to cleavage) xanthine-orange. Found at the Benallt mine in Wales.

**Cronstedtite**  $[Fe''_4Fe'''_2(OH)_8Si_2Fe'''_2O_{10}]$  is chemically an iron chlorite, but crystallographically related to kaolinite.<sup>103</sup> It is monoclinic(?) with  $a:b:c = 0.580:1:0.748$  and  $a$  5.48,  $b$  9.45,  $c$  7.08 Å (Gossner<sup>103</sup>) or hexagonal<sup>104</sup> with  $a$  5.48,  $c$  21.25 Å and  $a:c = 1:3.878$ . Crystals 3- or 6-sided pyramids; also fibrous; perfect 001 cleavage, somewhat elastic.  $H. = 3.5$ .  $G. = 3.45$ .  $F. = 5$ , with frothing. Gelatinizes with HCl. The optic plane is probably 010 and  $X$  is nearly normal to 001.  $(- )2E = 0^\circ$  ca.,  $N_Y = 1.80$  ca.,  $N_Z - N_X =$  strong. Again:<sup>102</sup>  $N_Y = N_Z = 1.721$  (with 3.98 MgO). Color coal to brownish or greenish black with dark olive-green streak, and  $X =$  dark reddish brown or emerald green,  $Y = Z =$  olive green to nearly opaque. Found with limonite, quartz, etc., in ore deposits, as at Kuttentberg, Bohemia.

**Strigovite**  $[H_2Fe''_2(OH)_2Si_2(Al,Fe)_2O_{10}]$  closely resembles chlorite in properties, but contains more silica. It is monoclinic(?) and pseudohexagonal in minute 6-sided prisms, and plates and fibers.  $H. = 1$ .  $G. = 3.14$ .  $F. = 6$ . Easily decomposed by acid.  $X$  (nearly) normal to plates;<sup>12</sup>  $(- )2V = 0^\circ$  ca.,  $N_X = 1.65$ ,  $N_Y = N_Z = 1.67$ ,  $N_Z - N_X = 0.02$ . Again:<sup>105</sup>  $(- )2V = 5-7^\circ$ ,  $N_X = 1.656$ ,  $N_Y$  and  $N_Z = 1.666$ . Color dark green with  $X =$  pale greenish,  $Y = Z =$  nearly opaque. Found as a coating of druses in granite, as at Striegau, Silesia.

<sup>102</sup> W. C. Smith, F. A. Bannister, and M. H. Hey: *Mineral. Mag.*, XXVII, 217 (1946).

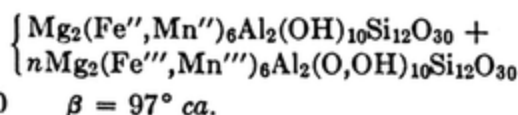
<sup>103</sup> B. Gossner: *Cent. Min.*, 1935A, 195.

<sup>104</sup> S. B. Hendricks: *Am. Mineral.*, XXIV, 529 (1939).

<sup>105</sup> D. P. Serdyuchenko: *Min. Abst.*, X, 501 (1949).

## STILPNOMELANE

MONOCLINIC



$$a:b:c = 0.557:1:2.570 \quad \beta = 97^\circ \text{ ca.}$$

COMP. Formula quite uncertain; K, Na, Ca, Ti often present; exchange of Tl for K may occur.<sup>106</sup> Oxidation of iron very variable. Tenor of Mg, Al, Si varies: manganostilpnomelane (*parsettensite*) is perhaps hexagonal.<sup>107</sup>

STRUC.<sup>106</sup>  $a$  5.39,  $b$  9.40,  $c$  sin  $\beta$  12.12 Å. Unit cell contains 8 Si atoms.

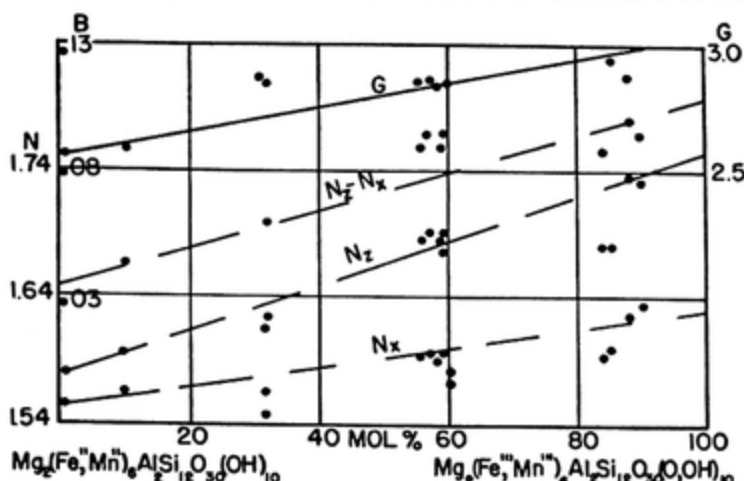


FIG. 271. Properties of stilpnomelane.

PHYS. CHAR. Lamellar with perfect 001 cleavage.  $H. = 1.5$  ca.  $G. = 2.7-3.0$ .

OPT. PROP. The axis X is sensibly normal to 001. Data follow (see Fig. 271):

	Grau- bünden <sup>108</sup>	Otago <sup>107</sup>	Sar- gans <sup>109</sup>	Lahn <sup>110</sup>	N. Wales <sup>111</sup>	Baern <sup>107</sup>	Otago <sup>107</sup>
(Fe,Mn)O =	34.43	25.55	29.61	25.13	16.24	13.34	3.86
Fe <sub>2</sub> O <sub>3</sub> =	0.35	4.12	8.48	13.33	22.47	21.64	31.67
(- )2V =	0°	0°	0°	0°	0°	0°	0°
N <sub>X</sub> =	1.546	1.551	1.561	1.565	1.595	1.597	1.625
N <sub>Y</sub> =	1.576	1.594	1.599	1.623	1.685	1.692	1.735
N <sub>Z</sub> =	1.576	1.594	1.599	1.623	1.685	1.692	1.735
N <sub>Z</sub> - N <sub>X</sub> =	0.030	0.043	0.038	0.058	0.090	0.095	0.110
G. =	2.59	2.62		2.82	2.85	2.85	2.83

*Ferrostilpnomelane* is green, *manganostilpnomelane* (or *parsettensite*) is yellow, and *ferristilpnomelane* is brown to black; all are pleochroic, as follows ( $X < Y$  and  $Z$ ):

	X	Y and Z
Ferrostilpnomelane	Pale yellow	Deep green
Manganostilpnomelane	Clear yellow to colorless	Light greenish yellow
Ferristilpnomelane	Bright golden yellow	Deep olive brown

<sup>106</sup> J. W. Gruner: *Am. Mineral.*, XXII, 209 and 912 (1937); also XXI, 204 (1936) and XXIX, 291 (1944).

<sup>107</sup> C. O. Hutton: *Mineral. Mag.*, XXV, 172 (1938).

<sup>108</sup> J. Jakob: *Schw. Min. Pet. Mit.*, III, 227 (1923).

<sup>109</sup> W. Epprecht: *Schw. Min. Pet. Mit.*, XXVI, 19 (1946).

<sup>110</sup> J. Holzner: *N. Jahrb. Min.*, Bl. Bd. LXVI, 213 (1933).

<sup>111</sup> A. F. Hallimond: *Mineral. Mag.*, XX, 193 (1924).

**OCCUR.** Stilpnomelane is found in iron ores with magnetite, quartz; also in schists with chlorite, epidote, albite, etc., as at Nassau, Germany; Antwerp, New York, etc.

**DIAG.** Chemically related to chlorite, but optically very similar to biotite, from which it differs <sup>107</sup> in having a less perfect basal cleavage (and a poor cleavage normal thereto), a strong golden-yellow tint (X), no mottled effect at extinction, more brittle flakes, and less definite X-ray pattern.

**Ganophyllite** <sup>112</sup>  $[Mn_7Al_2(OH)_{12}(Si_4O_{10})_2]$  is monoclinic with  $a:b:c = 0.413:1:1.831$ ,  $\beta = 93^\circ 21'$ . Crystals short prismatic with perfect 001 cleavage; also 010 cleavage. Closely related to stilpnomelane. H. = 4. G. = 2.84. F. = 3. Gelatinizes with HCl. Z = b.  $X \wedge c$  = small. Also in some cases, <sup>113</sup> Y = b (due to loss of water?). (-)2V = small <sup>114</sup> to moderate; <sup>112</sup>  $N_X = 1.545, 1.563, 1.573$ ,  $N_Y = 1.586, 1.593, 1.603, 1.612$ ,  $N_Z = 1.589, 1.593, 1.604, 1.612$ ,  $N_Z - N_X = 0.044, 0.030, 0.031$ . Color brown with X = yellowish brown, Y and Z = colorless. May be colorless in section. Found with manganese ores in Sweden and New Jersey.

**Bityite** <sup>115</sup>  $\{Ca_4(Li,Be)_4Al_8(OH)_{20}[(Si,Al)_4O_{10}]_3\}$  is pseudo-hexagonal in basal plates, or prismatic, with basal cleavage. H. = 5.5. G. = 3. F. = easy. Insoluble. Basal sections are divided into six sectors each normal to X. Each sector may show lamellar twinning parallel to a prism face. Extinction is at  $30^\circ$  on each side of the twinning plane. (-)2V = small.  $N_X = 1.62$ ,  $N_Y = 1.63$ ,  $N_Z = 1.64$ ,  $N_Z - N_X = 0.02 \pm$ . Color yellowish or white. Found in pegmatites with tourmaline, lepidolite, etc., at Mt. Bity, Madagascar. Differs from mica and prehnite in optic properties.

**CLINTONITE** <sup>116</sup> MONOCLINIC PRISMATIC <sup>117</sup>  $\left\{ \begin{array}{l} mCaMg_3(OH)_2Si_2Al_2O_{10} + \\ nCaMg_2(OH)_2AlSiAl_3O_{10} \end{array} \right.$   
 $a:b:c = 0.577:1:2.133$   $\beta = 100^\circ 3'$

**COMP.** <sup>118</sup> Usually contains a little Fe; also Na, etc.

**STRUC.** Space group <sup>117</sup>  $C2/m$ ;  $a$  5.21,  $b$  9.02,  $c$  19.24 Å.

**PHYS. CHAR.** Crystals like those of biotite; common multiple twinning on the mica law. Percussion and pressure figures interchanged in position as compared with the micas. Perfect 001 cleavage. H. = 3.5 on 001 and  $6 \perp 001$ . <sup>119</sup> G. = 3-3.15. F. = 7. Insoluble.

**OPT. PROP.** X nearly normal to 001; optic plane 010 (but normal to 010 in *seybertite*). Optic angle small; relief moderate. (-)2V =  $2^\circ$ - $40^\circ$ ,  $r < v$ ,  $N_X = 1.648$ ,  $N_Y = 1.659$ ,  $N_Z = 1.660$ ,  $N_Z - N_X = 0.012$ . With less iron <sup>120</sup> the index can be as low as 1.638.

<sup>112</sup> W. F. Foshag: *Am. Mineral.*, XXI, 63 (1936). Foshag's analysis gives  $Mn_5Al(OH)_2Si_7AlO_{20} \cdot 4H_2O$ .

<sup>113</sup> W. C. Smith: *Mineral. Mag.*, XXVIII, 343 (1948).

<sup>114</sup> E. S. Larsen and E. V. Shannon: *Am. Mineral.*, VII, 152 (1922), and IX, 238 (1924).

<sup>115</sup> Formula as given by H. Berman: *Am. Mineral.*, XXII, 386 (1937).

<sup>116</sup> *Xanthophyllite*, *brandisite*, and *seybertite* are sometimes considered varieties of clintonite; they are almost identical.

<sup>117</sup> F. Machatschki and F. Mussnug: *Naturw.*, XXX, 106 (1942).

<sup>118</sup> Formula as given by G. Koch: *Chem. Erde*, IX, 453 (1935).

<sup>119</sup> G. Switzer: *Am. Jour. Sci.*, CCXXXIX, 316 (1941).

<sup>120</sup> A. Laitakari: *Bull. Com. Géol. Finlande*, 54, 87 (1920).

Color leek to bottle green, reddish gray, reddish brown, copper red with  $X$  = reddish brown,  $Y$  and  $Z$  = green;  $X$  = orange-yellow,  $Y$  and  $Z$  = pale green;  $X$  = colorless,  $Y$  and  $Z$  = pale brownish yellow.

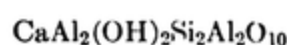
**OCCUR.** Clintonite is found in chlorite schists, in contact rocks, in limestone with serpentine, etc., as at Amity, New York.

**DIAG.** Clintonite differs from micas in the position of the percussion and pressure figures, the hardness, the brittleness, and the weaker birefringence. It differs from chlorite in stronger birefringence, greater hardness, brittleness, and weak dispersion. It differs from chloritoid in negative sign, small optic angle, and pleochroism.

**Kossmatite**<sup>121</sup>  $[\text{Ca}_3\text{MgAl}_2(\text{OH},\text{F})_9\text{Si}_3\text{AlO}_{10}]$  is much like clintonite.  $H. = 2.5$ .  $F. = 6$ . Nearly uniaxial and positive with  $(+2E = 14^\circ, N_X = 1.560, N_Y = 1.564, N_Z = ?$  (for  $529 \mu$ ). Colorless. Found in dolomite with corundum at a contact at Prilep, Serbia.

## MARGARITE

MONOCLINIC (PSEUDOHExAGONAL)



$$a:b:c = 0.575:1:1.093$$

$$\beta = 100^\circ 48'$$

**COMP.** May contain a little Fe, Mg, Na, K.

**STRUC.**<sup>122</sup>  $a$  5.12,  $b$  8.90,  $c$  9.73 Å.

**PHYS. CHAR.** Thin tabular to lamellar with perfect 001 cleavage. Common twinning on the mica law. Cleavage lamellae brittle. Percussion figure as in mica.  $H. = 3.5-4.5$ .  $G. = 3.0-3.1$ .  $F. = 6$ . Attacked by  $\text{H}_2\text{SO}_4$ .

**OPT. PROP.**  $Z = b$ ;  $X \wedge c = 6^\circ$  ca. See Fig. 272.  $(-2V = \text{small to } 67^\circ, r < v$ .  $N_X = 1.632$ ,  $N_Y = 1.643$ ,  $N_Z = 1.645$ ,  $N_Z - N_X = 0.013$  (Larsen<sup>123</sup>);  $N_X = 1.620$ ,  $N_Y = 1.629$ ,  $N_Z = 1.630$ ,  $N_Z - N_X = 0.010$  (Shannon<sup>123</sup>). See Fig. 273. Color grayish, reddish, white, pink, yellowish; colorless in thin section.

FIG. 272. The optic orientation of margarite.

**ALTER.** Margarite changes to a brownish yellow micaceous mineral known as *dudleyite*.

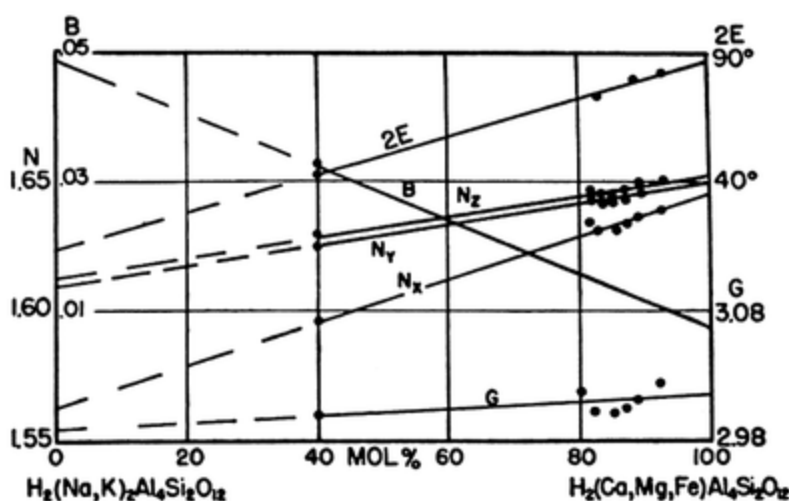


FIG. 273. Properties of margarite.

<sup>121</sup> O. H. Erdmannsdörffer: *Cent. Min.*, 1925A, 69.

<sup>122</sup> C. Mauguin: *C. R. Acad. Sci. Paris*, CLXXXVI, 879 (1928).

<sup>123</sup> E. V. Shannon: *Proc. U. S. Nat. Mus.*, LVIII, 469 (1920).

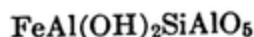
**OCCUR.** It is found in metamorphosed rocks with corundum, from which it may be derived; also in mica schist with tourmaline and staurolite, as at Sterzing, Tyrol; Chester, Massachusetts, etc.

**DIAG.** It differs from micas in its weaker birefringence and from chlorite and chloritoid in the absence of color in thin section.

**Ephesite**<sup>124</sup>  $[NaAl(OH)SiAlO_5]$  is probably soda-margarite.  $a$  5.16,  $b$  8.79 Å. Perfect 001 cleavage. Common twinning.  $H. = 5-7$ .  $G. = 3$ .  $(- )2E = 43^\circ$ ,  $r < v$ .  $N_X = 1.595$ ,  $N_Y = 1.625$ ,  $N_Z = 1.627$ ,  $N_Z - N_X = 0.032$ . Found near Ephesus.

## CHLORITOID

### MONOCLINIC PRISMATIC



$$a:b:c^{125} = 1.725:1:3.314 \quad \beta = 101^\circ 30'$$

**COMP.** Some Mg or Mn (or Ti?) may proxy for Fe'', and Fe''' for Al. With Mg it is called *sismondine*.

**STRUC.**  $a$  9.45,  $b$  5.48,  $c$  18.16 Å. U.C. 8.

**PHYS. CHAR.** Similar to mica in form and twinning. Basal cleavage not so perfect as in mica although accentuated by twinning. Imperfect 110 cleavage and 010 parting. Cleavage laminae not flexible.  $H. = 6.5$ .  $G. = 3.26-3.57$ .  $F. = 6$ , and becomes magnetic. Decomposed by  $H_2SO_4$ .

**OPT. PROP.** The optic plane<sup>126</sup> is 010;  $Z \wedge \perp 001 = 3^\circ-30^\circ$ .  $(+)2V = 36^\circ-68^\circ$  with distinct horizontal dispersion and  $r > v$  strong; strong crossed dispersion<sup>127</sup> in Idaho sample; a New York sample has abnormal dispersion with green on the convex side and yellow on the concave side of the isogyres.<sup>128</sup> See Fig. 274.  $N_X = 1.722$ ,  $N_Y = 1.725$ ,  $N_Z = 1.728$ ,  $N_Z - N_X = 0.006$ .  $Z \wedge \perp 001$  for red greater than for violet. Indices vary notably, doubtless with variations in composition; thus  $N_Y$  varies from 1.72 to 1.77 and  $N_Z - N_X$  from 0.007 to 0.016.

Color dark gray to greenish black with strong pleochroism, as follows:

X = Gray green	Colorless to pale greenish	Olive or grass green
Y = Slate blue	Indigo blue	Blue or pale green
Z = Pale yellow	Pale greenish brown	Yellow-green or pale yellow

**INCL.** Usually rich in inclusions, especially of quartz, but also of magnetite, ilmenite, rutile, tourmaline, etc.

**ALTER.** Chloritoid may alter to muscovite and penninite.

<sup>124</sup> F. C. Phillips: *Mineral. Mag.*, XXII, 482 (1931).

<sup>125</sup> I. H. Milne: *Am. Mineral.*, XXXIV, 422 (1949). A different orientation is given by F. Machatschi and F. Mussgnug: *Naturw.*, XXX, 106 (1942).

<sup>126</sup> Sometimes said to make a small angle with 010, making chloritoid triclinic. See Lane, Keller and Sharpless: *Am. Jour. Sci.*, CXLII, 499 (1891). Milne (*Am. Mineral.*, XXXIV, 422, 1949) reports that  $X = b$ .

<sup>127</sup> E. V. Shannon: *U. S. Nat. Mus. Bull.* 131, 377 (1926).

<sup>128</sup> T. F. W. Barth and R. Balk: *Am. Mineral.*, XIX, 345 (1934).

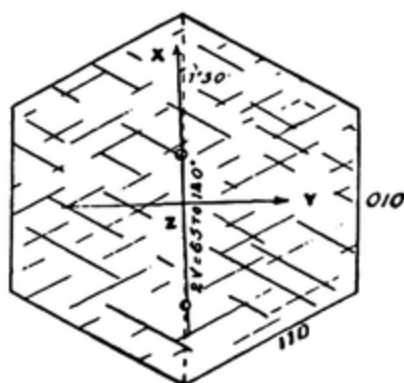


FIG. 274. The optic orientation of chloritoid.

**OCCUR.** It is found in schists, where it may be abundant, as at St. Marcel and Zermatt, Switzerland. It is also found as a hydrothermal alteration product in lavas in the Porcupine district of Ontario and at Kalgoorlie, West Australia, and also as a vein mineral in the Porcupine district.<sup>129</sup>

**DIAG.** Color, pleochroism, high relief, weak birefringence, large optic angle (as compared with chlorite), and strong dispersion are quite characteristic. The cleavages are numerous, but not micaceous; the laminae are not elastic or flexible; the specific gravity is high.

**Ottrelite** [(Mn,Fe)<sub>2</sub>Al<sub>3</sub>(OH)<sub>2</sub>Si<sub>5</sub>Al<sub>3</sub>O<sub>20</sub>?] is much like chloritoid, but is probably triclinic, having cleavages<sup>130</sup> the traces of which make angles of 40°, 50°, and 90° in 001.  $H. = 6-7$ .  $G. = 3.3$ .  $F. = 6$  to magnetic globule. Optic plane nearly parallel with 010;  $Z \wedge c = 12^\circ$  (varies to  $25^\circ$  ca.).  $N_Y = 1.73$ ,  $N_Z - N_X = 0.01$  ca. Color gray; streak gray or green; weakly pleochroic. Found in schists, as at Tintagel, Cornwall.

**Scawtite**<sup>131</sup> (2CaCO<sub>3</sub>·Ca<sub>2</sub>Si<sub>3</sub>O<sub>8</sub>?) is monoclinic with perfect 001 and poor 010 cleavages. Crystals 001 laminae.  $H. = 4.5-5$ .  $G. = 2.77$ . Attacked by weak HCl. The optic plane is 010;  $Z \wedge a = 29^\circ$ . (+)2V = 74°,  $N_X = 1.597$ ,  $N_Y = 1.606$ ,  $N_Z = 1.621$ ,  $N_Z - N_X = 0.024$ . Again:<sup>132</sup> (+)2V = 78°,  $N_X = 1.603$ ,  $N_Y = 1.609$ ,  $N_Z = 1.618$ ,  $N_Z - N_X = 0.015$ . Colorless with vitreous luster. Found in a contact zone at Scawt Hill, Ireland, and in Montana.

## (b) WITH ADDITIONAL ANIONS—HYDROUS

### APOPHYLLITE

DITETRAGONAL DIPYRAMIDAL



$$c/a = 1.76$$

**COMP.** Na may proxy for part of the K and OH for F; about half the water is lost at about 250°, the rest at higher temperatures.

**STRUC.** Space group<sup>133</sup>  $P4/mnc$ ;  $a$  9.00,  $c$  15.8 Å,  $c/a = 1.76$ . U.C. 2.

**PHYS. CHAR.** Crystals prismatic with {001} or {111}. Rare twinning on 111. Perfect 001 and poor 110 cleavages.  $H. = 4.5-5$ .  $G. = 2.3-2.4$ .  $F. = 1.5$  with exfoliation. Decomposed to slimy silica by HCl.

**OPT. PROP.** Uniaxial and positive, or less commonly negative; sometimes basal sections are divided into sectors some of which are biaxial, positive for red and negative for blue, with axial planes crossed as in brookite; the biaxial character may be produced by lateral pressure or change of temperature. Strikingly abnormal interference colors and interference figures are due to marked dispersion of the birefringence, which may be zero in any part of the spectrum, the corresponding color then being absent in the interference tints. The abnormal colors may disappear at about 275°, which suggests an inversion at that temperature. Cornu<sup>134</sup> reports that apophyllite with F is negative, has lower refringence, and, if biaxial, the dispersion is  $r > v$ , while apophyllite without F is positive, has higher refringence, and, if biaxial, the dispersion is  $r < v$ . But these conclusions need verification and are

<sup>129</sup> J. K. Gustafsen: *Am. Mineral.*, XXXI, 313 (1946).

<sup>130</sup> J. Mélon: *Mem. Acad. Roy. Belge, Cl. Sci.*, XVII, No. 4 (1938).

<sup>131</sup> C. E. Tilley: *Mineral. Mag.*, XXII, 222 (1930). Is the formula 2CaCO<sub>3</sub>·Ca<sub>2</sub>Si<sub>3</sub>O<sub>7</sub>(OH)?

<sup>132</sup> J. H. Taylor: *Am. Mineral.*, XX, 120 (1935).

<sup>133</sup> W. H. Taylor and St. Naray-Szabo: *Zeit. Krist.*, LXXVII, 146 (1931).

<sup>134</sup> F. Cornu: *Cent. Min.*, 1906, 79.



opposed in part by the data of Wenzel,<sup>135</sup> who found that isotropic and negative apophyllites have higher refringence than positive types.

	Positive			Isotropic (Na)			Negative		
	N <sub>O</sub>	N <sub>E</sub>	N <sub>E</sub> -N <sub>O</sub>	N <sub>O</sub>	N <sub>E</sub>	N <sub>E</sub> -N <sub>O</sub>	N <sub>O</sub>	N <sub>E</sub>	N <sub>O</sub> -N <sub>E</sub>
Li	1.532	1.534	0.002	1.5381	1.5384	0.0003	1.5415	1.5415	0.0000
Na	1.535	1.537	0.002	1.5418	1.5418	0.0000	1.5433	1.5429	0.0004
Tl	1.537	1.539	0.002	1.5438	1.5438	0.0000	1.5448	1.5439	0.0009

Colorless, white, or tinted by impurities. Colorless in thin section.

**ALTER.** A cloudy alteration product may be calcite or kaolin or hydrous silica; <sup>136</sup> in the last case it is not opal or chalcedony, but a skeleton of the apophyllite with variable indices; uniaxial negative with  $N_O = 1.449$  or more,  $N_E = 1.439$  or more,  $N_O - N_E = 0.006$  ca.

**OCCUR.** Apophyllite is found in cavities in basalts or other rocks, often associated with zeolites; also as an alteration product of wollastonite, as at Poona, India; Finbo, Sweden; Bergen Hill, New Jersey; and New Almaden, California.

**DIAG.** It has a higher refringence than common in zeolites; it differs from uniaxial zeolites in having a perfect basal cleavage. The tetragonal form and abnormal interference colors are also quite characteristic.

**Manandonite** ( $2Li_2O \cdot 7Al_2O_3 \cdot 2B_2O_3 \cdot 6SiO_2 \cdot 12H_2O$ ?) is perhaps related to cookeite; it is pseudo-hexagonal and apparently orthorhombic with perfect basal cleavage.  $G. = 2.89$ .  $F. =$  easy. Attacked by  $H_2SO_4$ .  $Z$  (nearly) normal to cleavage and optic plane parallel to pseudo-hexagonal edges in sectors of basal sections.  $(+ )2E = 25^\circ - 30^\circ$ ,  $N_Y = 1.6$  ca.,  $N_Z - N_X = 0.014$ . Colorless. Found in pegmatite in Madagascar.

**Gyrolite** [ $Ca_4(OH)_2Si_6O_{15} \cdot 3H_2O$ ] is hexagonal (scalenohedral?) with  $c/a = 1.936$ . Crystals lamellar with perfect basal cleavage.  $H. = 3-4$ .  $G. = 2.34-2.45$ .  $F. =$  difficult, with swelling. Soluble in acid. Uniaxial negative with  $N_O = 1.540-1.548$ ,  $N_O - N_E = 0.01$  (Cornu <sup>137</sup>). Also distinctly biaxial with basal plates divided into sectors and  $N_X = 1.518$ ,  $N_Y = 1.523$ ,  $N_Z = 1.532$ ,  $N_Z - N_X = 0.015$  (Müller <sup>138</sup>). Colorless, white. Found at times with apophyllite. Known at Collinward, Ireland; Faröe Islands; Poona, India; etc. *Centrallassite* <sup>139</sup> is essentially the same with  $G. = 2.51$  and  $(- )2V =$  small,  $X$  normal to cleavage,  $N_X = 1.535$ ,  $N_Y = 1.548$ ,  $N_Z = 1.549$ ,  $N_Z - N_X = 0.014$ . Found in pegmatite at Crestmore, California. *Truscottite* <sup>139</sup> differs only in containing  $Mg(Ca:Mg = 4:1)$  and has  $N_X = 1.528$ ,  $N_Y = N_Z = 1.549$ ,  $N_Z - N_X = 0.021$ ; again, <sup>140</sup>  $N = 1.560$ . Found at Benkulen, Sumatra. *Reyerite* is closely related to gyrolite, but contains less water and some alumina and soda. It has the same crystal form with  $G. = 2.5-2.55$  and  $N_O = 1.5645$ ,  $N_E = 1.5590$ ,  $N_O - N_E = 0.0055$ . Colorless. Found in Greenland, India, California, etc.

<sup>135</sup> A. Wenzel: *N. Jahrb. Min.*, Bl. Bd. XLI, 565 (1917).

<sup>136</sup> E. H. Bailey: *Am. Mineral.*, XXVI, 565 (1941).

<sup>137</sup> F. Cornu: *Sitz. Akad. Wiss. Wien*, CXVI, 1213 (1907).

<sup>138</sup> J. Koenigsberger and W. J. Müller: *N. Jahrb. Min.*, Bl. Bd. XLIV, 402 (1907); perhaps not gyrolite since the indices given are apparently too low and make the mineral positive.

<sup>139</sup> E. P. Flint, H. F. McMurdie, and L. S. Wells: *J. Res. Nat. Bur. Stand.*, XXI, 617 (1938).

<sup>140</sup> J. A. Grutterink: *Min. Abst.*, III, 271 (1927).

**Errite** <sup>141</sup>  $[\text{Mn}_4(\text{OH})_4\text{Si}_4\text{O}_{10} \cdot 3\text{H}_2\text{O}]$  is hexagonal(?) with platy basal cleavage. Related to parsettensite.  $G. = 2.68$ . Uniaxial negative with  $N_O = 1.575$ ,  $N_E = 1.547$ ,  $N_O - N_E = 0.028$ . Found at Alp Parsettens, Switzerland.

**VERMICULITE** MONOCLINIC  $\left\{ \begin{array}{l} m(\text{Mg,Fe})_4(\text{OH})_4\text{Si}_4\text{O}_{10} \cdot 4\text{H}_2\text{O} + \\ n(\text{Mg,Fe})_3(\text{Al,Fe})(\text{OH})_2\text{Si}_3\text{AlO}_{10} \cdot 4\text{H}_2\text{O} \end{array} \right.$   
 $a:b:c = 0.58:1:3.14$   $\beta = 93^\circ 15'$

COMP. Mg can be replaced by Ni by base exchange artificially; <sup>142</sup> some Ni found in nature; tenor of water variable.

STRUC. Space group <sup>143</sup>  $Cc(?)$ ;  $a$  5.33,  $b$  9.18,  $c$  28.85 Å.

PHYS. CHAR. Lamellar with perfect 001 cleavage.  $H. = 1.5$ .  $G. = 2.4$ . Exfoliates with much swelling when heated.

OPT. PROP. X is normal to 001. Data follow: <sup>144</sup>

	Maryland	Macon, N. C.	Webster, N. C.	Webster, N. C.	Colorado <sup>145</sup>
$\text{Fe}_2\text{O}_3 = 4.24$		5.61	3.40	2.74	6.35
$\text{FeO} = 0.68$			...	0.41	8.61
$\text{NiO} = 0.28$		?	5.34	11.25	$\text{TiO}_2$ 1.74
$(- )2V = 0^\circ$		$0^\circ$	$0^\circ-8^\circ, r > v$ weak	$0^\circ$	Small
$N_X = 1.525$		1.540	1.542	1.561	?
$N_Y = 1.545$		1.560	1.573	1.581	$> 1.586$
$N_Z = 1.545$		1.560	1.573	1.581	?
$N_Z - N_X = 0.020$		0.020	0.031	0.020	?

Color brown, with bronze-yellow luster; also green. Pleochroic with  $X =$  colorless,  $Y = Z =$  pale brown. Nickelian vermiculite is green with  $X =$  pale green,  $Y = Z =$  yellowish to brownish green.

OCCUR. Vermiculite may be an alteration product of biotite; found at Libby, Montana; Macon, North Carolina; in Madagascar; etc. *Jefferisite* <sup>146</sup> or *hydrobiotite* seems to be an interlayered aggregate of vermiculite and biotite.

**Connarite** <sup>146</sup>  $[(\text{Ni,Mg})_8(\text{OH})_4(\text{Si}_4\text{O}_{10})_3 \cdot 6\text{H}_2\text{O}]$  is monoclinic with perfect 001 cleavage.  $H. = 2.5-3$ .  $G. = 2.5 \pm$ . X normal to cleavage.  $(- )2V = 0^\circ$  ca.,  $N_X = 1.56$  ca.,  $N_Y = N_Z = 1.59$  ca.,  $N_Z - N_X = 0.03 \pm$ . Color yellowish green, weakly pleochroic. Found with siderite, quartz, and phosphates at Röttis, Voigtland.

**Pholidolite**  $[\text{K}(\text{Mg,Fe})_6(\text{OH})_4\text{Si}_7\text{AlO}_{20} \cdot 3\text{H}_2\text{O}]$  is monoclinic in pseudo-hexagonal flakes with perfect 001 cleavage.  $H. = 4$ .  $G. = 2.41$ . X is sensibly normal to 001.  $(- )2V = 0^\circ-20^\circ$ ,  $N_X = 1.503$ ,  $N_Y = N_Z = 1.545$ ,  $N_Z - N_X = 0.042$ . Color green; nearly colorless in thin section. Found in contact zones in Sweden.

<sup>141</sup> J. Jakob: *Schw. Min. Pet. Mit.*, III, 227 (1923).

<sup>142</sup> C. S. Ross, E. V. Shannon, and F. A. Gonyer: *Econ. Geol.*, XXIII, 528 (1928).

<sup>143</sup> S. B. Hendricks and M. E. Jefferson: *Am. Mineral.*, XXIII, 851 (1938).

<sup>144</sup> E. V. Shannon: *Am. Jour. Sci.*, CCXV, 20 (1928).

<sup>145</sup> V. C. Alderson: *Colo. Sch. Mines Circ. Inf.*, 1923.

<sup>146</sup> Considered to be a variety of schuchardite by K. Spangenberg: *Min. Abst.*, VIII, 14 (1941). Perhaps a variety of garnierite. See E. F. Alexeeva and M. N. Godlevsky: *Min. Abst.*, VII, 214 (1939).

## MONTMORILLONITE

The claylike mineral called montmorillonite varies much in composition. One end-member <sup>147</sup> is probably  $Al_8(OH)_{24}Si_{16}O_{24}(OH)_{16}$  or  $4Al_2O_3 \cdot 16SiO_2 \cdot 20H_2O$  or  $Al_8(OH)_8(Si_4O_{10})_4 \cdot 16H_2O$  (= *leuverrierite* <sup>148</sup>). By substitution of Al for Si (and increase of

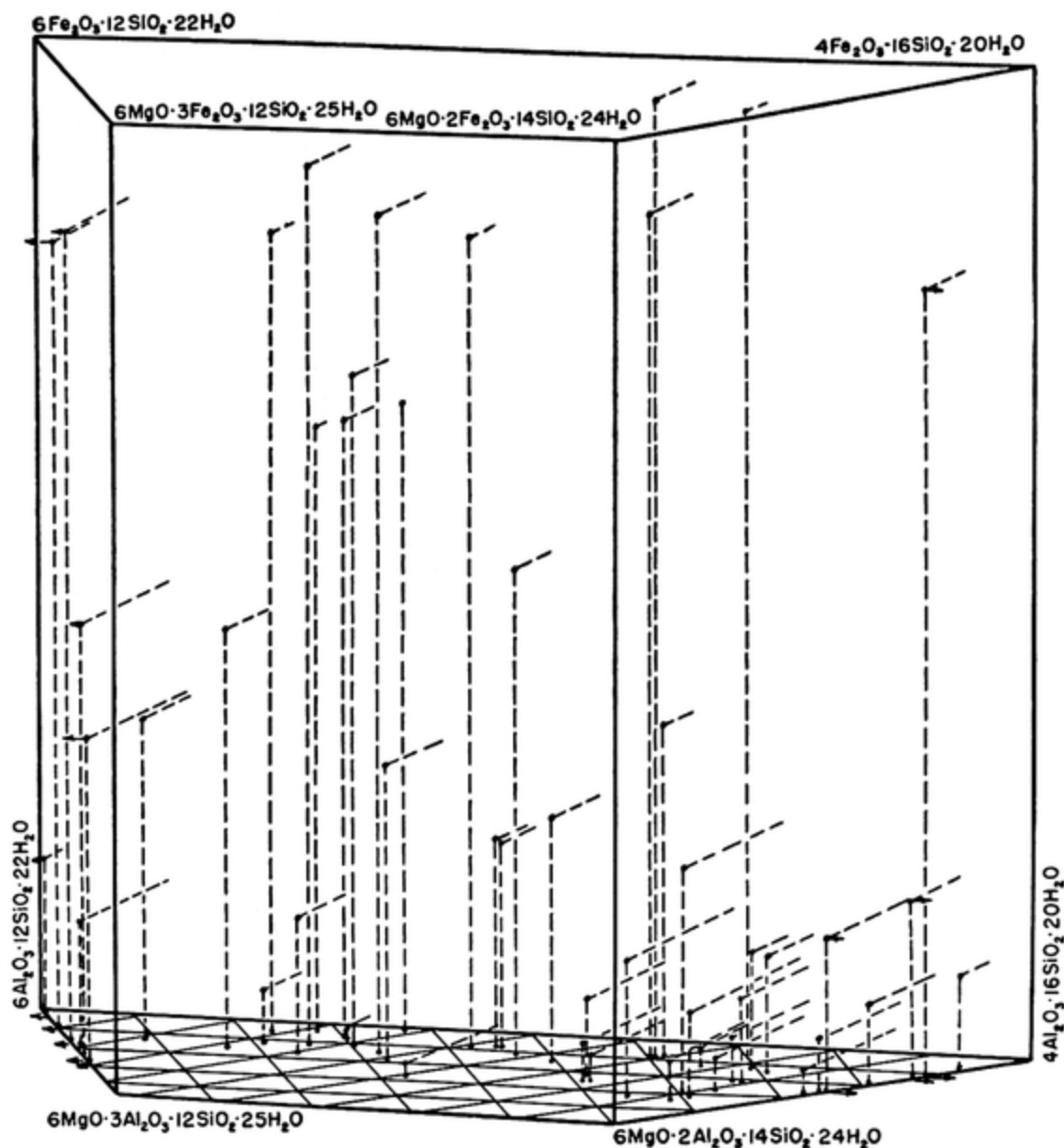


FIG. 275. Composition of the montmorillonite system.

$H_2O$ ) this varies to  $6Al_2O_3 \cdot 12SiO_2 \cdot 22H_2O$  or  $Al_8(OH)_8Si_{12}Al_4O_{36}(OH)_4 \cdot 16H_2O$  (= *beidellite*). Montmorillonite can be made artificially <sup>149</sup> containing up to 15.30 per cent of  $MgO$ ; this means that half the Al atoms (of beidellite) have been re-

<sup>147</sup> C. E. Marshall: *Zeit. Krist.*, XCI, 433 (1935).

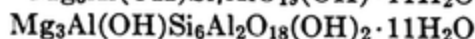
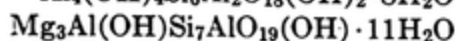
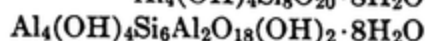
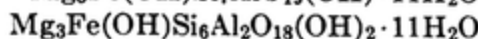
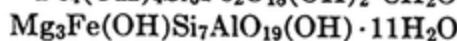
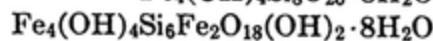
<sup>148</sup> A. N. Winchell: *Am. Mineral.*, XXX, 510 (1945).

<sup>149</sup> W. Noll: *Chem. Erde*, X, 129 (1936).

placed by Mg atoms, and this end-member has the composition:  $^{150} 6\text{MgO} \cdot 3\text{Al}_2\text{O}_3 \cdot 12\text{SiO}_2 \cdot 25\text{H}_2\text{O}$  or  $\text{Mg}_6\text{Al}_2(\text{OH})_2\text{Si}_{12}\text{Al}_4\text{O}_{36}(\text{OH})_4 \cdot 22\text{H}_2\text{O}$ . By a similar replacement of (Si by Al and) Al by Mg in leverrierite a fourth end-member seems to be  $6\text{MgO} \cdot 2\text{Al}_2\text{O}_3 \cdot 14\text{SiO}_2 \cdot 24\text{H}_2\text{O}$  or  $\text{Mg}_6\text{Al}_2(\text{OH})_2\text{Si}_{14}\text{Al}_2\text{O}_{38}(\text{OH})_2 \cdot 22\text{H}_2\text{O}$ .<sup>151</sup> Further, four more end-members result from the replacement of Al by Fe'''; these belong to the *nontronite* end of the variations in composition.  $\text{Fe}_8(\text{OH})_{11}(\text{Si}_4\text{O}_{10})_4 \cdot 16\text{H}_2\text{O}$  may be called chloropal. See Fig. 275. It is probable that another group of four end-members results from replacement of Al by Cr; samples probably illustrating this have been called *volchonskoite*. Other minor variations in composition in montmorillonite include replacement of Si by (a little) P, and perhaps by Fe''' and Ti, and of Al by Ti, Fe'', Mn, Ca, and N. The tenor of water varies considerably.

**MONTMORILLONITE**MONOCLINIC <sup>152</sup>

$$a:b:c = 0.575:1:1.7 \text{ ca.}$$

**Leverrierite****Beidellite****Nontronite****Chloropal****Canbyite(?)**

STRUC. For montmorillonite <sup>152</sup> without Fe''':  $a$  5.15,  $b$  8.95,  $c$  15–15.5 Å; for *nontronite*  $a$  5.23,  $b$  9.11,  $c$  15–15.5 Å.

PHYS. CHAR. Crystals thin lamellar or vermicular, often compact; perfect basal cleavage.  $H. = 1.5$ .  $G. = 2.5$ – $2.6$ .  $F. = 5$  ca. with swelling, but for *nontronite*  $F. = 7$ . Attacked by acids.

OPT. PROP. The optic plane is 010;  $X$  is (nearly) normal to 001.  $(- )2V = 0^\circ$  to  $33^\circ$  (rarely large, even exceeding  $90^\circ$ ). Optic properties <sup>148</sup> vary with tenor of  $\text{H}_2\text{O}$ , etc., but much more with tenor of  $\text{Fe}_2\text{O}_3$ . Data follow (see Fig. 276).

	IDAHO	OTAY	ARKAN- SAS	SUIFU	ALTAI	SANDY RIDGE	HARZ	WOODY	URALS
100Fe'''									
$\div (\text{Fe}''' + \text{Al}) =$	1.4	3.1	5.9	9.3	42.9	63.9	81.9	86	87.4
$(- )2V =$		16°–24°	16°	12°–25°	30°			66°	26°
$N_X =$	1.488	1.492	1.517	1.543	1.559	1.54	1.589	1.57	1.585
$N_Y =$			1.549	1.5	1.588–		1.600	1.59	1.593
$N_Z =$	1.513	1.513	1.549	1.565	1.588	1.57	1.610	1.60	1.608
$N_Z - N_X =$	0.025	0.021	0.032	0.022	0.029	0.03	0.021	0.03	0.023

Dehydration raises the indices; for example,  $N_Y$  at  $15^\circ = 1.585$ , at  $75^\circ = 1.615$ , at  $160^\circ = 1.655$ , at  $290^\circ = 1.69$ .

<sup>150</sup> C. S. Ross and S. B. Hendricks (*U. S. Geol. Surv. Prof. Paper* 205B, 1945) have given evidence that Mg can proxy for even more Al in the montmorillonite system, which therefore probably includes *saponite*, *griffithite*, and *sauconite* (*Am. Mineral.*, XXXI, 411, 1946).

<sup>151</sup> The exact tenor of  $\text{H}_2\text{O}$  is variable and uncertain.

<sup>152</sup> G. Nagelschmidt: *Mineral. Mag.*, XXV, 140 (1938).

Without Fe montmorillonite is colorless, but it is often colored by iron dark olive green to yellow, orange, or brown; pleochroic with colors as follows:

X	Y	Z
Colorless	Dark brown	Clear brown
Pale yellow	Olive green	Yellowish to bright green
Yellow-green	Yellow-green	Brown to olive green
Nearly colorless		Yellow to greenish yellow
Yellow-brown		Pale yellow

**OCCUR.** Montmorillonite is found in some schists, in gouge clays, in "bentonite," in some veins; it may be an alteration product. Found at Millac and Montmorillon, France; Branchville, Connecticut; etc.

*Volchonskoite*<sup>153</sup>  $[(Cr, Fe, Al)_2O_3 \cdot 3SiO_2 \cdot nH_2O]$  seems to be a chromian nontronite. Unstable in water. It is lamellar. H. = 2.5. G. = 2.2–2.3. F. = 7, but it turns

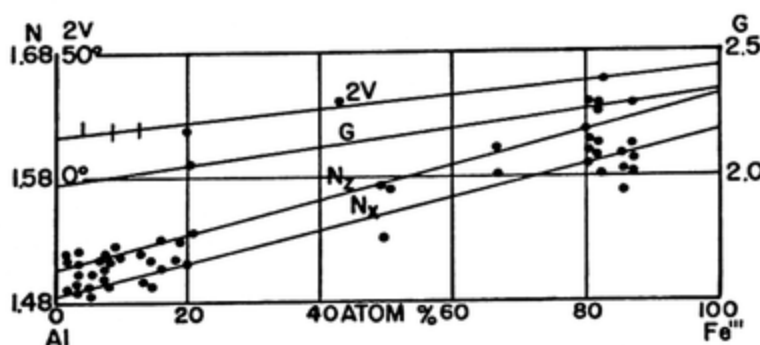


FIG. 276. Properties of the montmorillonite series.

black. Gelatinizes with HCl.  $(-)2V = \text{small}$ ,<sup>154</sup>  $N_X = 1.551$ ,  $N_Z = 1.564$ ,  $N_Z - N_X = 0.013$ . Again:  $N_Y = 1.585$  ca.,  $N_Z - N_X = \text{moderate}$ . Also isotropic (impure?) with  $N = 1.520$ – $1.546$ —Kiselev<sup>155</sup>. Color bluish to grass green. Found in clay at Sverdlovsk, U.S.S.R.

**Saponite**<sup>156</sup>  $[(Mg, Al, Fe)_3(OH)_2(Si, Al)_4O_{10}]$  is closely related to montmorillonite and probably belongs to that system.<sup>157</sup> It has perfect basal cleavage. Soft. G. = 2.26 ca. F. = 6. Attacked by  $H_2SO_4$ . X normal to cleavage. Negative with  $2V = 0^\circ$  to very small.  $N_X = 1.490$ ,  $N_Y = 1.525$ ,  $N_Z = 1.527$ ,  $N_Z - N_X = 0.037$  (Larsen<sup>12</sup>). Again:  $N_Y = 1.55$  or  $1.56$ ,  $N_Z - N_X = 0.01$  ca. (Larsen<sup>12</sup>); also  $N_X = 1.479$ ,  $N_Y = 1.510$ ,  $N_Z = 1.511$ ,  $N_Z - N_X = 0.032$  (Larsen<sup>12</sup>). *Griffithite* is a variety of saponite rich in iron ( $Fe_2O_3$  7.32 and  $FeO$  7.83) which has  $(-)2V = 0^\circ$ – $40^\circ$ ,  $N_X = 1.485$ ,  $N_Y = 1.569$ ,  $N_Z = 1.572$ ,  $N_Z - N_X = 0.087$  (Steiger<sup>158</sup>); it is pleochroic with X = clear yellow, Y = olive green, Z = brownish green. *Bowlingite* is a fibrous variety of saponite;<sup>159</sup> it is easily soluble in HCl;  $(-)2E = 0^\circ$ – $40^\circ$ ,

<sup>153</sup> D. P. Serdyuchenko: *Min. Abst.*, V, 486 (1934).

<sup>154</sup> V. P. Ivanova: *Min. Abst.*, VII, 427 (1940).

<sup>155</sup> A. I. Kiselev: *Min. Abst.*, IX, 267 (1946).

<sup>156</sup> Saponite and sauconite included here (although anhydrous) because they are so closely related to montmorillonite.

<sup>157</sup> C. Palache and H. E. Vassar: *Am. Mineral.*, X, 417 (1925).

<sup>158</sup> E. S. Larsen and George Steiger: *J. Wash. Acad. Sci.*, VII, 11 (1917).

<sup>159</sup> S. Caillère: *Min. Abst.*, VI, 141 (1935).

$N_Y = 1.6$  ca.,  $N_Z - N_X = 0.025$  ca. Bowlingite is an alteration product of olivine in basic igneous rocks; it may orient itself on olivine as shown in Fig. 277. Saponite is found in cavities in igneous rocks and in serpentine, as at the Ahmeek Mine, Michigan. Griffithite is found at Cahuenga Pass, California. Bowlingite is found in basic igneous rocks, as at Blackburn, Scotland, and in northern Michigan.

**Sauconite**<sup>160</sup>  $[(Zn,Mg,Al,Fe)_3(OH)_2(Si,Al)_4O_{10}]$  is closely related to saponite and probably belongs to the montmorillonite system. Perfect basal cleavage. Soft.  $(- )2V = \text{small}(?)$ ,  $N_X = 1.550-1.575$ ,  $N_Y = ?$ ,  $N_Z = 1.592-1.615$ ,  $N_Z - N_X = 0.035-0.042$ . Sauconite is the essential component of zinc clays; found in the Saucon valley, Pennsylvania; at Leadville, Colorado; near Zinc, Arkansas; Meeker's Grove, Wisconsin; etc.

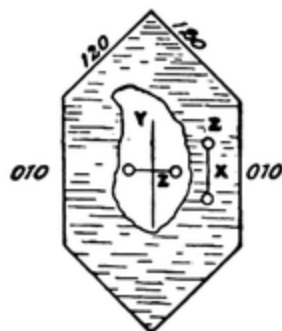


FIG. 277. Relation of bowlingite to olivine.

**Anauxite**<sup>161</sup>  $[Al_3(OH)_5Si_4O_{10} \cdot H_2O]$  is monoclinic and closely related to kaolinite—seems to form an isomorphous series with it. Crystals vermicular. Perfect basal cleavage.  $H. = 2-2.5$ .  $G. = 2.52$ .  $Z = b$ ,  $X \wedge c = 2^\circ$ .  $(- )2V = 0^\circ-42^\circ$ ,  $r > v$ ,  $N_X = 1.559$ ,  $N_Y = 1.564$ ,  $N_Z = 1.565$ ,  $N_Z - N_X = 0.007$ . Colorless. Luster pearly. Probably forms by alteration of biotite.

**Canbyite**<sup>162</sup>  $[Fe^{III}_4(OH)_8Si_4O_{10} \cdot 4H_2O]$  is related to kaolinite, but contains iron and more water.  $Z$  normal to cleavage.  $(- )2V = \text{small}$ .  $N_X = 1.562$ ,  $N_Y = 1.580$ ,  $N_Z = 1.582$ ,  $N_Z - N_X = 0.020$ .  $N_Y$  also varies from 1.552 to 1.595 (unexplained). Color golden to amber brown, not pleochroic. Found in a contact deposit at Wilmington, Delaware.

**Hisingerite**  $(Fe_2O_3 \cdot 2SiO_2 \cdot nH_2O)$  is perhaps the amorphous equivalent of canbyite.  $H. = 3-3.5$ .  $G. = 3$ .  $F. = 6$ . Decomposed by  $HCl$ . Isotropic with  $N = 1.44-1.66$  (Larsen<sup>12</sup>);  $1.52-1.73$  (Gordon<sup>163</sup>). Also finely fibrous with  $(- )2V = 0^\circ$  to small;  $N_X = 1.715$ ,  $N_Z = 1.730$  (Gordon<sup>163</sup>). Black with brown streak, but may be claret red for a few minutes after fresh fracture underground. Orange to golden brown in section. Found as an alteration product in ore deposits, as at Långban, Sweden; near Helsingfors, Finland; at Gap Mine, Pennsylvania.

**Halloysite**  $[Al_4(OH)_8Si_4O_{10} \cdot nH_2O]$  is apparently amorphous but the electron microscope<sup>164</sup> proves it is crystalline. Crystals elongated tablets or needles.  $H. = 1-2$ .  $G. = 2.1$  (to 2.6 after dehydration at  $110^\circ$ ). Isotropic (apparently) with  $N = (1.49 \text{ to } 1.532 \text{ (with } 4H_2O) \text{ and } 1.55 \text{ (with } 2H_2O \text{—then called } metahalloysite^{165}).$  Color white or tinted. Found in beds and veins as a constituent of clay, as near Liège, Belgium.

<sup>160</sup> C. S. Ross: *Am. Mineral.*, XXXI, 411 (1946).

<sup>161</sup> V. T. Allen: *Am. Mineral.*, XIII, 145 (1928) and C. S. Ross and W. F. Foshag: *Am. Mineral.*, XIII, 153 (1928). S. B. Hendricks: *Zeit. Krist.*, XCV, 247 (1936).

<sup>162</sup> A. C. Hawkins and E. V. Shannon: *Am. Mineral.*, IX, 1 (1924).

<sup>163</sup> S. G. Gordon: *Proc. Acad. Sci. Phila.*, XCVI, 279 (1944).

<sup>164</sup> L. T. Alexander, G. T. Faust, S. B. Hendricks, H. Insley, and H. F. McMurdie: *Am. Mineral.*, XXVIII, 1 (1943).

<sup>165</sup> M. N. Godlevsky: *Min. Abst.*, X, 371 (1948).



C. INOSILICATES<sup>1</sup> (CHAINS)1. Type formula  $A_m(BX_3)_n$  Single chains

## ANHYDROUS

*Astrolite*<sup>2</sup>  $[H_2(Na,K)_2Fe''(Al,Fe''')_2Si_5O_{15}]$  is orthorhombic; it is in globular forms with stellate structure; distinct cleavage parallel to the plates.  $H. = 3.5$ .  $G. = 2.78$ .  $F. = 3.5$ . Insoluble in acid.  $X$  normal to plates.  $(- )2V = 30^\circ$ ,  $r > v$ .  $N_X = 1.570$ ,  $N_Y = 1.594$ ,  $N_Z = 1.597$ ,  $N_Z - N_X = 0.027$ . Color greenish yellow with  $X =$  nearly colorless,  $Y = Z =$  siskin green. Found in xenoliths in diabase in Saxony.

*Taramellite*  $(Ba_4Fe''Fe'''_4OSi_{10}O_{30})$  is orthorhombic(?); fibrous, with perfect 100 cleavage parallel to fibers; parting normal to cleavage.  $H. = 5.5$ .  $G. = 3.92$ . The optic plane is parallel to fibers and normal to cleavage;  $Z$  parallel to fibers.  $(+)2E = 75^\circ 40'$ ,  $r > v$  distinct.  $N_X = 1.77$ ,  $N_Y = 1.774$ ,  $N_Z = 1.83$ ,  $N_Z - N_X = 0.06$ . Color reddish brown with  $X = Y =$  flesh red,  $Z =$  blackish brown. Found in limestone near a contact at Candoglia, Italy.

*Hyalotekite*  $(Ca_3Ba_3Pb_3B_2Si_{12}O_{36})$  is orthorhombic(?) with two cleavages at  $90^\circ$ .  $H. = 5-5.5$ .  $G. = 3.8$ . Insoluble in HCl. The optic plane is parallel to the intersection of the two cleavages.  $(+)2V =$  small,  $r < v$  strong.  $N_X = 1.963$ ,  $N_Y = 1.963$ ,  $N_Z = 1.966$ ,  $N_Z - N_X = 0.003$ . Colorless or gray. Found in ore deposits at Långban, Sweden.

*Chkalovite*  $(Na_2BeSi_2O_6)$  is orthorhombic.<sup>3</sup> It has one distinct and two poor cleavages.  $H. = 6$ .  $G. = 2.66$ .  $F. =$  easy, to colorless glass. Soluble in acid. Optic plane parallel to the distinct cleavage.  $(+)2V = 78^\circ$ ,  $N_X = 1.544$ ,  $N_Y = 1.546$  calc.,  $N_Z = 1.549$ ,  $N_Z - N_X = 0.005$ . Colorless. Found in veins in igneous rock of the Kola peninsula, U.S.S.R.

*Ramsayite*<sup>4</sup>  $(Na_2TiSi_2TiO_9)$  is orthorhombic pyramidal with  $a:b:c = 0.603:1:0.356$ . Crystals short needles with distinct 010 cleavage.  $H. = 6$ .  $G. = 3.43$ .  $F. =$  easy. Insoluble except in HF.  $X = b$ ,  $Y = a$ .  $(-)2V = 38-40^\circ$ ,  $r > v$  distinct.  $N_X = 1.91$ ,  $N_Y = 2.01$ ,  $N_Z = 2.03$ ,  $N_Z - N_X = 0.12$ . Brown to black and weakly pleochroic with  $X$  and  $Y =$  pale reddish yellow,  $Z =$  pale yellow. Found in pegmatite, as in Greenland.

## MULLITE

## ORTHORHOMBIC DIPYRAMIDAL



$$a:b:c = 0.986:1:?$$

COMP.<sup>5</sup>  $Al_2O_3:SiO_2$  ratio varies from 3:2 to 2:1.  $Fe'''$  and Ti may be present.

STRUC. Space group<sup>6</sup> probably  $Pmmm$ ;  $a$  probably<sup>7</sup> 7.49,  $b$  7.63,  $c$  2.87 Å.

<sup>1</sup> The pyroxenes are inosilicates; the classification of other minerals included here in the group C1 is doubtful and based largely on their formulas.

<sup>2</sup> R. Reinisch: *Cent. Min.*, 1904, 108.

<sup>3</sup> V. I. Gerasimovsky: *C. R. Acad. Sci. U.R.S.S.*, XXII, 259 (1939); *Am. Mineral.*, XXV, 380 (1940); *Min. Abst.*, VII, 314 (1940).

<sup>4</sup> N. V. Belov: *Min. Abst.*, IX, 45 (1944). Belov's  $abc$  changed to  $bac$  to make  $b > a$ . *Lorenzenite* is probably the same. See T. G. Sahama: *Am. Mineral.*, XXXII, 59 (1947).

<sup>5</sup> H. P. Rooksby and J. H. Partridge: *Min. Abst.*, VIII, 14 (1941).

<sup>6</sup> M. E. Nahmias: *Zeit. Krist.*, LXXXV, 355 (1933).

<sup>7</sup> W. H. Taylor: *Zeit. Krist.*, LXVIII, 503 (1928).

**PHYS. CHAR.** Crystals prismatic with vertical elongation and distinct 010 cleavage.  $G = 3.0 \pm$ .

**OPT. PROP.** The optic plane is 010;  $Z = c$ . Properties vary notably with varying tenor of  $Fe_2O_3$  and  $TiO_2$ . Data follow:

$Fe_2O_3$	$TiO_2$	(+)2V	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$	F - C ( $N_Z$ )	AUTHORITY
0.0(art.)		45°-50°	1.642	1.644	1.654	0.012		Bowen <sup>8</sup>
0.50	0.79	?	1.651	?	1.668	0.017		Bowen <sup>9</sup>
0.86	1.12	?	1.653	?	1.672	0.019		Bowen <sup>9</sup>
?	1.86	?	1.648	?	1.679	0.031	0.023	Sawatari <sup>10</sup>

Colorless to pink or red with  $X = Y$  = colorless and  $Z$  = rose-pink.

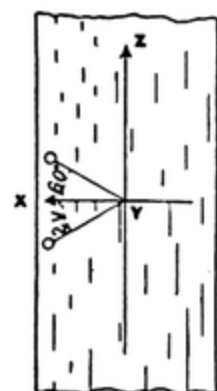
**INVER.** A second phase<sup>11</sup> has  $X = c$ ,  $N_X = 1.600$ ,  $N_Z = 1.610$ ; found in slags and firebricks.

**OCCUR.** Mullite is found in phyllite xenoliths in igneous rocks. It is rare in nature, but very common in porcelain, etc., being the only compound of  $Al_2O_3$  and  $SiO_2$  stable at high temperature.

**DIAG.** Mullite closely resembles sillimanite, but in types with  $N_Z$  as high as the minimum value in sillimanite mullite has much stronger dispersion (about 0.023 in mullite and 0.012 in sillimanite).

**Carpholite** [ $MnAl_2(OH)_4Si_2O_6$ ?] is orthorhombic; crystals unknown. Fibers with perfect 010 (and 110?) cleavage.  $H = 5-5.5$ .  $G = 2.9$ .  $F = 3.5$ . Nearly insoluble in HCl. The optic plane is 100;  $Z = c$ . See Fig. 278.  $(-)2V = 60^\circ$  ca.,  $N_X = 1.62$  ca.,  $N_Y = 1.63$ ,  $N_Z = 1.64$  ca.,  $N_Z - N_X = 0.022$ . Elongation positive. Color straw to wax yellow; in thin section colorless to yellow with  $X = Y$  = golden yellow,  $Z$  = colorless.

FIG. 278. The optic orientation of carpholite.



The maximum absorption is therefore normal to the elongation. Found in veins with quartz, as at Meuville, France. Differs from ardennite in its positive elongation, lower relief, and fusibility.

## PYROXENE GROUP

The minerals of the pyroxene group are very closely related in crystallographic and other physical characters, as well as in chemical composition, although they crystallize in two different crystal systems (orthorhombic and monoclinic). In all of them the common form is the unit prism with interfacial angles of about  $87^\circ$  and  $93^\circ$ , and there are good cleavages parallel to these faces. Chemically the pyroxenes are meta-silicates of magnesium, iron, manganese, and calcium, with double silicates of sodium or lithium and aluminum or ferric iron.

**PHYS. CHAR.** The pyroxenes commonly crystallize in rather short

<sup>8</sup> N. L. Bowen and E. G. Zies: *Jour. Amer. Ceram. Soc.*, VII, 238 (1924).

<sup>9</sup> N. L. Bowen, J. W. Greig, and E. G. Zies: *Jour. Wash. Acad. Sci.*, XIV, 183 (1924).

<sup>10</sup> M. Sawatari: *Min. Abst.*, VI, 70 (1935). W. Eitel (*Zt. anorg. Chem.*, LXXXVIII, 173, 1914) gives  $N_Y(F) - N_Y(C) = 0.026$  with  $N_Z = 1.664$ .

<sup>11</sup> W. Hugill: *Min. Abst.*, VIII, 95 (1941).

prismatic forms with good prismatic cleavages, and rather common twinning on 100. They have a hardness of 5 to 7, and a density of 2.8 to 3.7.

OPT. PROP. The optic plane is parallel to 010 in orthorhombic and most monoclinic pyroxenes; in monoclinic types the axis  $Z$  makes with

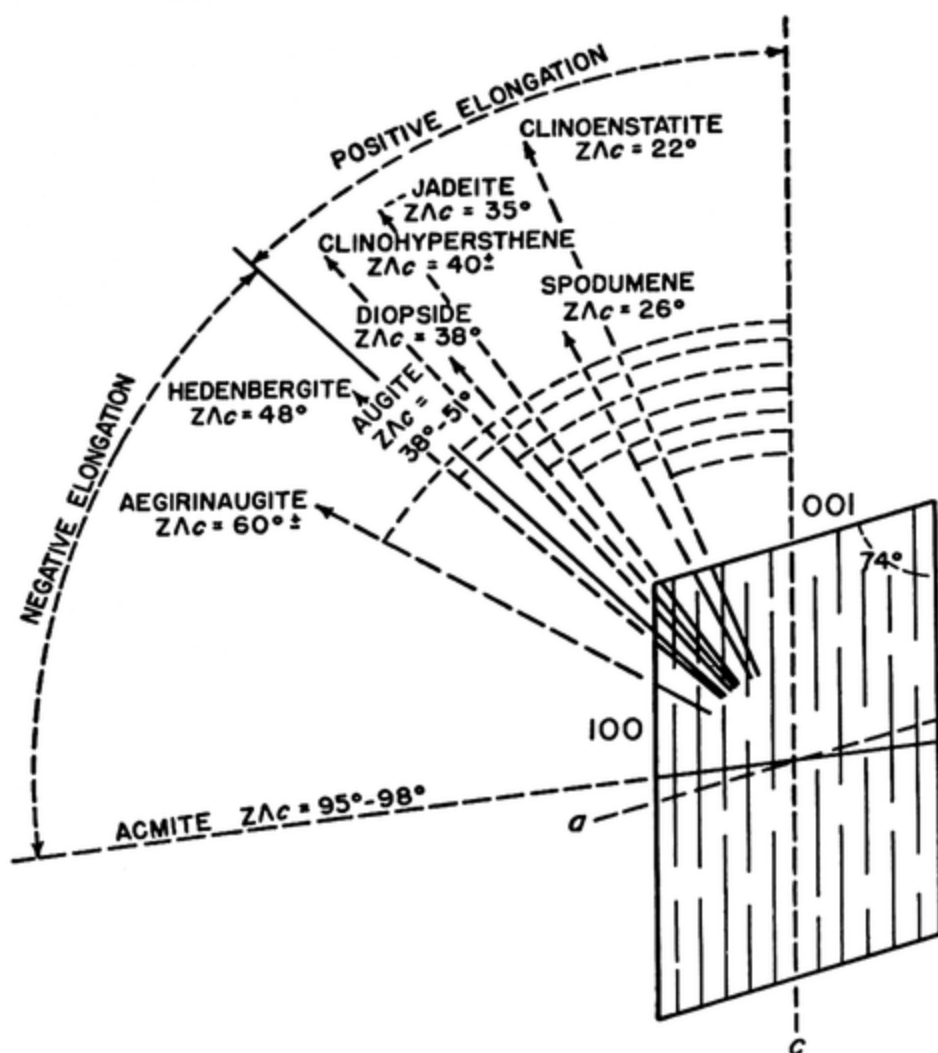


FIG. 279. Extinction angles in monoclinic pyroxenes.

the vertical crystal axis  $c$  an angle of  $22^\circ$  to  $95^\circ$  in the obtuse angle  $\beta$ . These angles are shown in Fig. 279. Pyroxenes may have parting parallel to 100 or to 001. The relief is always distinct, and the birefringence varies from 0.009 in enstatite to 0.029 in diopside and 0.052 in acmite. The angle of the optic axes is usually large ( $54^\circ$  to  $90^\circ$ ), but in pigeonite it is very small.

Pyroxene is usually dark colored (black, green, brown) but may be yellow, blue, or even white. In thin section it is usually colorless or nearly so. But soda-pyroxenes have a distinct green color and pleochroism, and other special types (like titanaugite) have peculiar colors.

**ALTER.** Pyroxene alters rather readily, especially to amphibole or chlorite.

**OCCUR.** Pyroxenes are essential constituents of many igneous rocks, and occur in nearly all such rocks. They are also found in various metamorphic rocks, both regional and contact, and sparingly in some sediments and meteorites.

**DIAG.** Pyroxenes differ from amphiboles as follows:

Pyroxenes	Amphiboles
Cleavage angle about $87^\circ$ and $93^\circ$	Cleavage angle about $124^\circ$ and $56^\circ$
Crystals usually short prismatic	Crystals usually long prismatic
Maximum extinction angle in vertical zone $30^\circ$ – $54^\circ$ , except alkaline types with unusual colors	Maximum extinction angle in vertical zone $0^\circ$ – $25^\circ$ , except certain alkaline types with unusual colors
Most types optically +	Most types optically –
Color and pleochroism usually weak	Color and pleochroism usually strong
Alter to amphibole, etc.	Alter to chlorite, etc.

**CLASS.** Orthorhombic pyroxene is called enstatite, and it varies from enstatite,  $\text{MgSiO}_3$ , to ferrosilite,  $\text{FeSiO}_3$ . Monoclinic pyroxenes include clinoenstatite, pyroxene proper, and spodumene. Hess<sup>12</sup> has argued cogently that clinoenstatite and augite do not form a continuous isomorphous system, and no evidence of a series from spodumene to other pyroxenes is known, though such a series may be possible. In tabular form the pyroxenes may be arranged as follows:

ORTHORHOMBIC		COMPOSITION	
Enstatite	Enstatite	$\text{MgSiO}_3$	
	Hypersthene	$(\text{Mg,Fe})\text{SiO}_3$	
	Orthoferrosilite	$\text{FeSiO}_3$	
MONOCLINIC			
Clinoenstatite	Clinoenstatite	$\text{MgSiO}_3$	
	Clinohypersthene	$(\text{Mg,Fe})\text{SiO}_3$	
	Pigeonite	$m(\text{Mg,Fe})\text{SiO}_3 + n\text{CaSiO}_3$	
	Clinoferrosilite	$\text{FeSiO}_3$	
Polyaugite <sup>13</sup>	Diopside	$\text{CaMgSi}_2\text{O}_6$	
	Hedenbergite	$\text{CaFeSi}_2\text{O}_6$	
	Johannsenite	$\text{CaMnSi}_2\text{O}_6$	
	Augite	$\text{Ca}(\text{Mg,Fe,Mn})\text{Si}_2\text{O}_6$ with $(\text{Mg,Fe})\text{Si}_2\text{O}_6$ and $(\text{Al,Fe})_2\text{O}_3$	
	Acmite	$\text{NaFeSi}_2\text{O}_6$	
	Jadeite	$\text{NaAlSi}_2\text{O}_6$	
Spodumene		$\text{LiAlSi}_2\text{O}_6$	

<sup>12</sup> H. H. Hess: *Am. Mineral.*, XXVI, 515 and 573 (1941).

<sup>13</sup> Some name seems to be needed for this group of pyroxene subspecies; clino-pyroxene is not satisfactory since it includes clinoenstatite and spodumene. Augite is much the commonest variety in this group; the group includes ordinary augite, leucaugite, ferroaugite, magaugite, titanaugite, and aegirinaugite, so *polyaugite* seems appropriate (the other varieties all being closely related to augite).



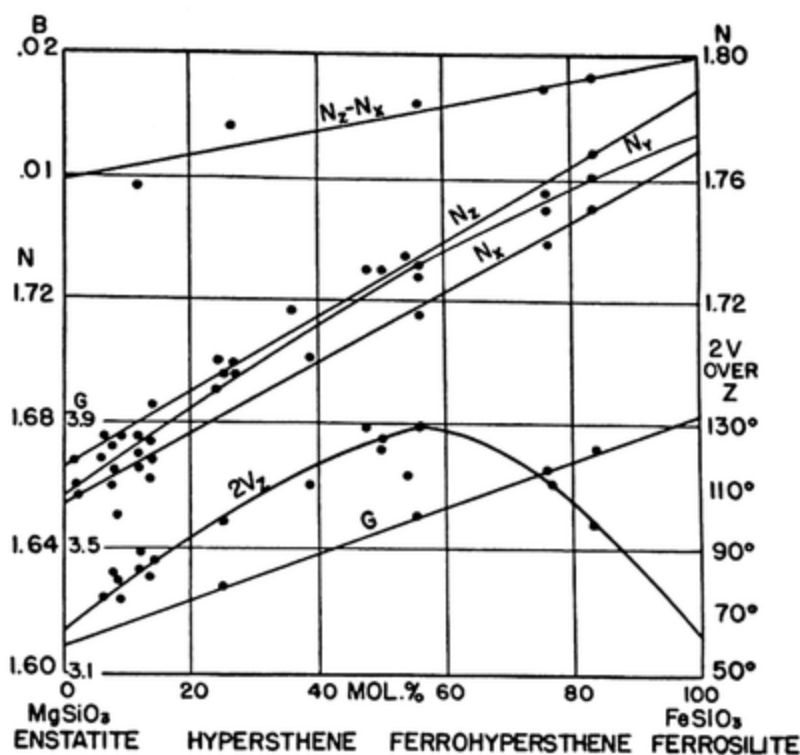


FIG. 283. Properties of the enstatite series.

birefringence increase with increase in iron as shown in Fig. 283 and illustrated as follows:

% FeSiO <sub>3</sub> =	1.8	12.4	38.8	56.1	76.8	83.6	100
2V over Z =	58°	75°	109°	129°	112°	99°	60° calc.
N <sub>X</sub> =	1.657	1.666	?	1.715	1.738	1.750	1.77 calc.
N <sub>Y</sub> =	1.660	1.670	?	1.728	1.749	1.760	1.785 calc.
N <sub>Z</sub> =	1.667	1.675	1.703	1.731	1.755	1.768	1.79 calc.
N <sub>Z</sub> - N <sub>X</sub> =	0.010	0.009	?	0.016	0.017	0.018	0.02 calc.
G. =	?	3.25	3.49	3.60	3.75	3.83	3.9 calc.

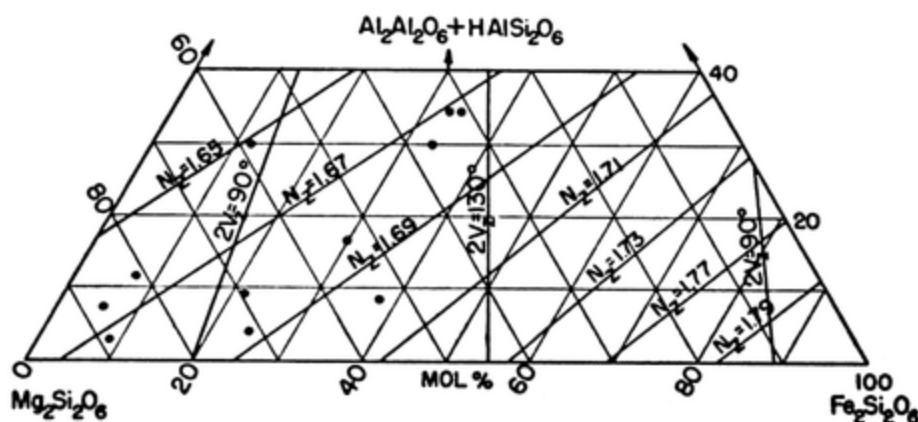


FIG. 284. Properties of aluminian enstatite.



Alumina has much less effect upon the properties. This is shown (only approximately, because of insufficient data) in Fig. 284.

Color white or gray (with no iron), yellow, brown, green (usually darker with increasing iron, but variable). Enstatite is colorless in thin section; bronzite is colorless or nearly so, but in thick sections it has X = pale yellow, Y = brownish yellow, Z = bright green; hypersthene is reddish or greenish in thin section, usually pleochroic. Examples follow:

X = Clear red	Brownish red	Hyacinth red	Reddish fawn
Y = Yellowish brown	Clear red	Straw yellow	Light fawn
Z = Clear green	Bottle green	Sky blue	Greenish gray

$\beta$ -Hypersthene is a very rare variety<sup>16</sup> in which the optic plane is 001, the elongation is  $\pm$ , and the optic angle is large. A layer containing  $\alpha$  and  $\beta$  types may be uniaxial.

INVER. Enstenite inverts<sup>17</sup> to clinoenstenite at below 1100°.

INCL. Inclusions are not rare; they may be gaseous, liquid, or other minerals, such as magnetite, apatite, quartz, etc. Bronzite contains inclusions regularly arranged which give it a submetallic bronzy luster. See Fig. 285.

ALTER. Enstenite alters rather easily to a variety of antigorite called *bastite*, which is geometrically oriented on the original pyroxene. It may also alter to a kind of amphibole called *uralite*, or, rarely, to talc.

OCCUR. Enstenite is a common constituent of some basic igneous rocks such as norite, andesite, etc., as well as of serpentine derived from them. It is also found in some rocks produced by contact metamorphism and in some crystalline schists. Finally, it is important in some meteorites.

DIAG. Enstenite differs from monoclinic pyroxenes in having parallel extinction in vertical sections. Enstatite differs from hypersthene in optic sign.



FIG. 285. Schiller inclusions in hypersthene (bronzite). After Lacroix.

<sup>15</sup> B. Rama Rao and L. Rama Rao: *Indian Acad. Sci.*, V, 290 (1937).

<sup>16</sup> A. Lacroix: *Minéral. France*, IV (1910).

<sup>17</sup> N. L. Bowen and J. F. Schairer: *Am. Jour. Sci.*, CCXXIX, 151 (1935).

CLINOENSTENITE	MONOCLINIC PRISMATIC	(Mg,Fe,Ca)SiO <sub>3</sub>
	$a:b:c$ $\beta$	
<b>Clinoenstatite</b> <sup>18</sup>	1.033:1:0.591      106°	MgSiO <sub>3</sub>
<b>Clinohypersthene</b>		(Mg,Fe)SiO <sub>3</sub>
<b>Pigeonite</b>		$m(\text{Mg,Fe})\text{SiO}_3 + n\text{CaSiO}_3$
<b>Clinoferrosilite</b> <sup>19</sup>	1.079:1:0.583      108° 29'	FeSiO <sub>3</sub>

COMP. Besides the series from MgSiO<sub>3</sub> to FeSiO<sub>3</sub>, 5–15 mol. % CaSiO<sub>3</sub> is present in pigeonite (as well as nearly as much Al<sub>2</sub>O<sub>3</sub>). Minor amounts of TiO<sub>2</sub>, MnO, etc., are not rare. The relations between names and

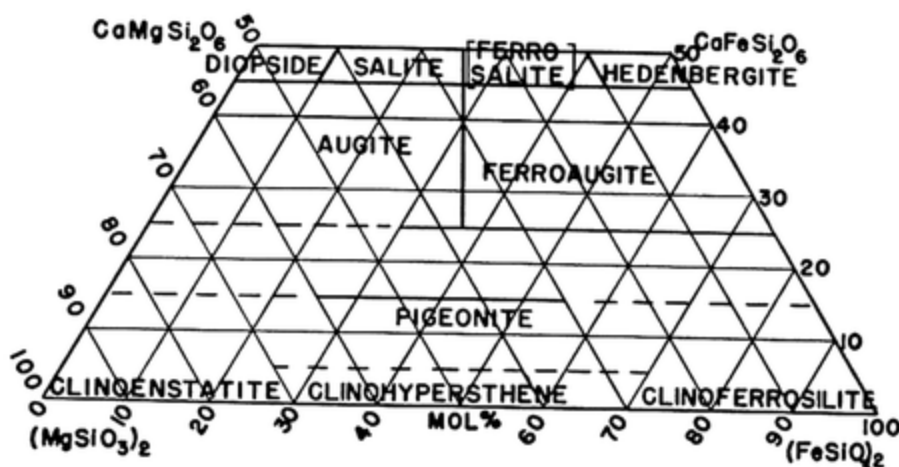


FIG. 286. Nomenclature of clinoenstatite and polyaugite. [After H. H. Hess: *Am. Mineral.*, XXVI, 515 and 573 (1941).]

composition are shown in Fig. 286, about as proposed by Hess.<sup>12</sup> Augite, as well as pigeonite, normally contains about 5–15% Al<sub>2</sub>O<sub>3</sub> (not shown in the diagram).

STRUC. Space group *C2/c*;  $a$  9.7,  $b$  8.8,  $c$  5.24 Å. U.C. 8.

PHYS. CHAR. Crystals short prismatic or {100} tablets. Good 110 cleavages at about 88°. Very common twinning on 100.  $H. = 6$ .  $G. = 3.19$  (MgSiO<sub>3</sub>) to about 3.6. Stable<sup>17</sup> from about 1100° to about 1300° (varying with the composition); metastable at lower temperatures.

OPT. PROP. The optic plane is normal to 010, except in pigeonite with more than about 5–10 mol. % CaSiO<sub>3</sub>. The extinction angle ( $Z \wedge c$ ) varies from  $-22^\circ$  in MgSiO<sub>3</sub> through a maximum of  $-42^\circ$  at about 55 mol. % FeSiO<sub>3</sub> to about  $-30^\circ$  for FeSiO<sub>3</sub> (see Fig. 287). The optic sign is positive, and the optic angle varies from  $53^\circ$  in MgSiO<sub>3</sub> to very small in FeSiO<sub>3</sub> and in pigeonite. The refringence is high to extreme, and the birefringence varies from about 0.01 for clinoenstatite

<sup>18</sup> F. Zambonini: *Zeit. Krist.*, XLVI, 1 (1909).

<sup>19</sup> N. L. Bowen: *J. Wash. Acad. Sci.*, XXIII, 83 (1933).

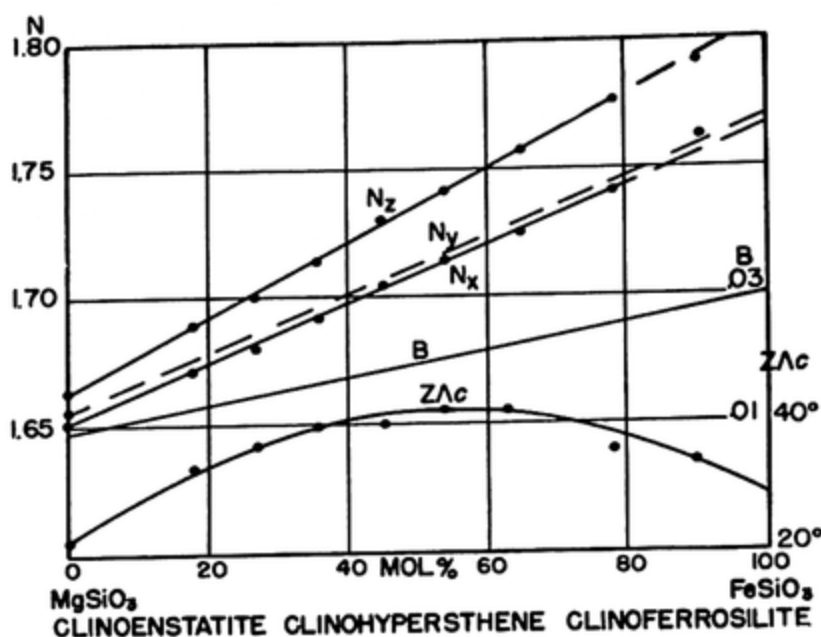


FIG. 287. Properties of clinoenstatite.

to about 0.03 for clinoferrosilite. These variations are shown in Fig. 287 and illustrated in the following data:<sup>20</sup>

	(+)2V	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$	$Z \wedge c$	G.	Mol. % FeSiO <sub>3</sub>
Clinoenstatite	53°	1.651	1.654	1.660	0.009	22°	3.19	0
Clinohypersthene	?	1.680	?	1.700	0.02	36.5°	?	27
Clinohypersthene	?	1.725	?	1.755	0.03	42°	?	63
Clinoferrosilite	Small	1.763	?	1.794	0.031	34°	?	90 ca.
Pigeonite <sup>21</sup> (8% CaO)	0°	1.713	1.713	1.738	0.024	?	?	48
Pigeonite <sup>22</sup> (7% CaO)	15°-20°	1.690	1.691	1.711	0.011	44°	3.42	42
Pigeonite <sup>23</sup> (3.8% CaO)	0°	1.714	1.714	1.744	0.030	40°	3.42	61

At high temperature there seems to be a continuous series from clinoenstatite through pigeonite to diopside; the properties of this series are shown in Fig. 288. The discontinuity between clinoenstatite and the diopside-hedenbergite series at ordinary temperature is indicated again in Fig. 289, which also shows some of the properties of these series.

Clinoenstatite is colorless, yellow, brown, greenish, black. In section colorless or weakly pleochroic with X = yellowish green, Y = brownish pink, Z = greenish white; again, X = Y = smoky brown, Z = pale yellow; again X = pink or flesh colored, Y = pale yellowish green, Z = pale green.

<sup>20</sup> N. L. Bowen: *Am. Jour. Sci.*, CCXXX, 481 (1935). Important data given also by H. H. Hess: *Am. Mineral.*, XXXIV, 621 (1949).

<sup>21</sup> H. Kuno: *J. Geol. Soc. Japan*, XLVII, 347 (1940); *Min. Abst.*, VIII, 160 (1941).

<sup>22</sup> W. Wahl: *Tsch. Min. Pet. Mit.*, XXVI, 18 (1907).

<sup>23</sup> A. F. Hallimond: *Mineral. Mag.*, XVII, 97 (1914).

**ALTER.** Changes to serpentine rather easily; other modes of alteration are similar to those of augite.

**OCCUR.** Clinoenstatite is found rarely in some igneous rocks; also in

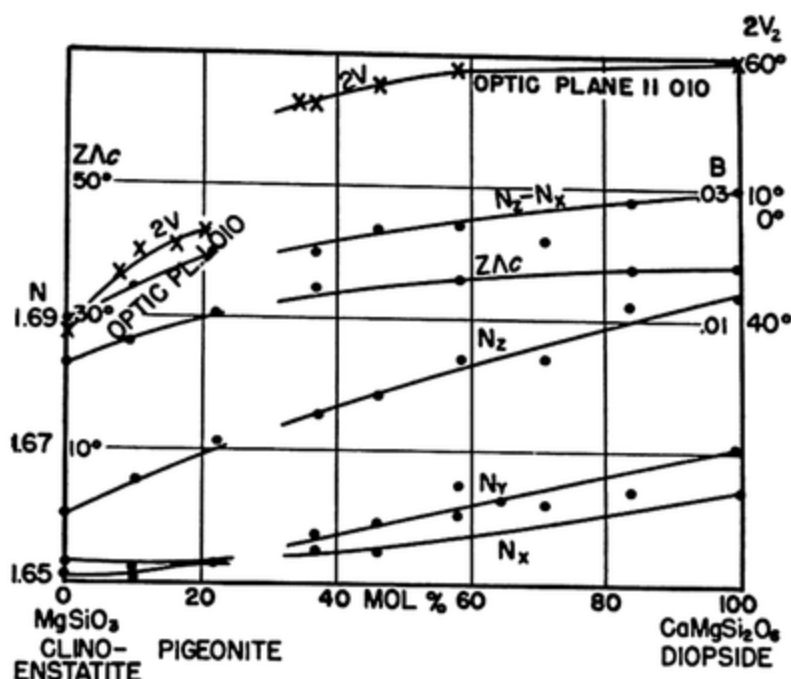


FIG. 288. Properties of the clinoenstatite-diopside discontinuous series.

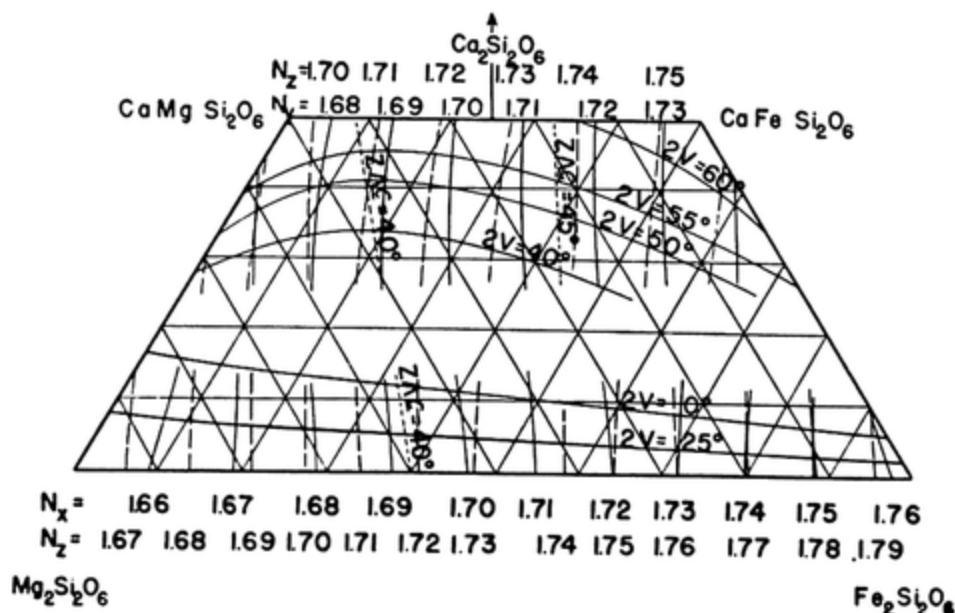
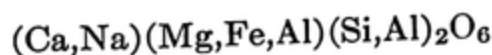


FIG. 289. Properties of the clinoenstatite and diopside-hedenbergite systems.

meteorites. Pigeonite is perhaps the commonest variety, being found especially in basalt, andesite, gabbro, etc.

**DIAG.** Clinoenstatite nearly always shows lamellar twinning on 100; the small optic angle is quite distinctive, except in clinoenstatite and that has a small extinction angle.

## POLYAUGITE



## MONOCLINIC PRISMATIC

 $a:b:c$  $\beta$ 

<b>Diopside</b>	1.091:1:0.589	105° 51'	$CaMgSi_2O_6$
<b>Hedenbergite</b>	1.091:1:0.584	105° 25'	$CaFeSi_2O_6$
<b>Johannsenite</b>			$CaMnSi_2O_6$
<b>Augite</b>	1.092:1:0.584	105° 50'	$Ca(Mg,Fe)Si_2O_6$ with $Mg_2Si_2O_6$ and $Al_2Al_2O_6$
<b>Acmite</b> <sup>24</sup>	1.099:1:0.601	106° 49'	$NaFeSi_2O_6$
<b>Jadeite</b>	1.103:1:0.613	107° 16'	$NaAlSi_2O_6$

COMP. Variations of composition are common and important. As shown in Fig. 286, *salite* and *ferrosalite* are types in the diopside-hedenbergite series. Augite is salite with additional  $(Mg,Fe)SiO_3$ , and *ferroaugite* bears the same relation to ferrosalite; both also usually contain 5–15%  $Al_2O_3$ , with or without a similar tenor of  $Fe_2O_3$ . There seems to be continuous variation from augite to acmite, and intermediate types have been called *aegirinaugite*. *Urbanite* is similar but contains no  $Al_2O_3$ . *Chloromelanite* contains jadeite, acmite, and diopside molecules. Augite with very little iron and very little color is known as *leucaugite*. Augite with a notable tenor of  $TiO_2$  is known as *titanaugite*.  $MnO$  may proxy for part of the  $FeO$  in salite and ferrosalite; the mineral is then called *schefferite*; with additional  $ZnO$  it is called *zinkian schefferite* or *jeffersonite*. A chrome diopside <sup>25</sup> with  $2V = 71^\circ$  has been found.  $CaTiAl_2O_6$  is miscible <sup>26</sup> to at least 10 mol. per cent with  $CaMgSi_2O_6$ .

STRUC. Space group  $C2/c$ ; for diopside: <sup>27</sup>  $a$  9.71,  $b$  8.89,  $c$  5.24 Å; other varieties very nearly the same. U.C. 4.

PHYS. CHAR. Crystals usually short prisms with  $\{100\}$  and  $\{010\}$  terminated by  $\{111\}$  or  $\{001\}$ . See Figs. 290–293. Twinning on 100 common (Fig. 294), usually giving distinct 100 parting, if lamellar. Basal lamellar twinning and parting (Fig. 295) can be produced by shearing strains. Samples with good 100 parting are called *diallage*; those with distinct 001 parting are called *malacolite*. Distinct 110 cleavages at  $87^\circ$ .  $H. = 5-6$ .  $G. = 3.275$  ( $CaMgSi_2O_6$ ) to 3.55 ( $CaFeSi_2O_6$ ).  $F. = 1391^\circ$  ( $CaMgSi_2O_6$ ),  $1180^\circ$  ( $CaFeSi_2O_6$ —after changing to olivine and quartz),  $990^\circ$  ( $NaFeSi_2O_6$ ),  $1060^\circ$  ( $NaAlSi_2O_6$ ).

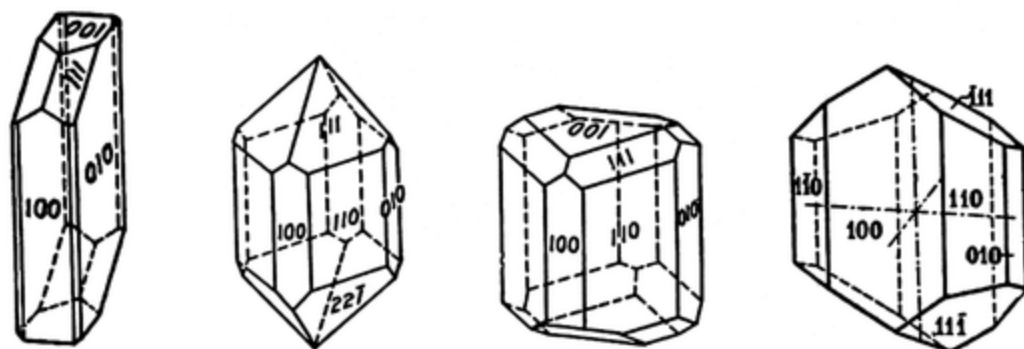
OPT. PROP. The optic plane is parallel to 010 and the optic angle is large in all polyaugites. The extinction angle ( $Z \wedge c$ ) varies from about

<sup>24</sup> Also known as *aegirine*.

<sup>25</sup> G. M. Stockley: *Min. Abst.*, X, 291 (1948).

<sup>26</sup> T. F. W. Barth: *N. Jahrb. Min.*, Bl. Bd. LXIV, A, 217 (1931).

<sup>27</sup> B. E. Warren and J. Biscoe: *Zeit. Krist.*, LXXX, 391 (1931).



FIGS. 290-293. Crystal habits of polyaugite.

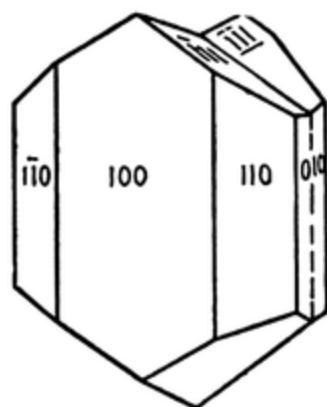


FIG. 294. Simple twinning on 100 in polyaugite.



FIG. 295. Lamellar twinning on 001 in polyaugite.



FIG. 296. The optic orientation of diopside.

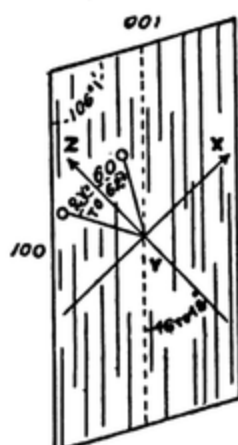


FIG. 297. The optic orientation of hedenbergite.

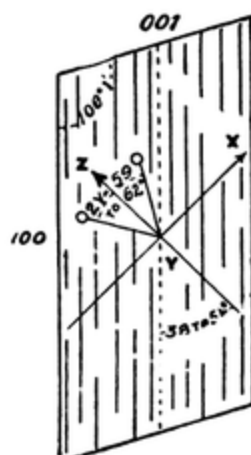


FIG. 298. The optic orientation of augite.

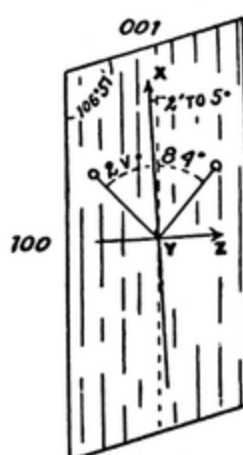


FIG. 299. The optic orientation of aegirine.

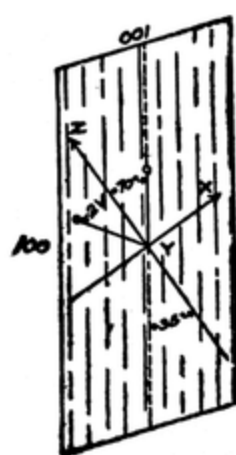


FIG. 300. The optic orientation of jadeite.



$-38^\circ$  in diopside to more than  $-90^\circ$  in acmite, but in common augite it is usually near  $-45^\circ$ . The optic sign is positive except in acmite. The optic angle is about  $60^\circ$ , decreasing to about  $40^\circ$  with increasing magnesia and increasing to about  $80^\circ$  with increasing soda. The dispersion is  $r > v$  (weak) except in jadeite; inclined dispersion with

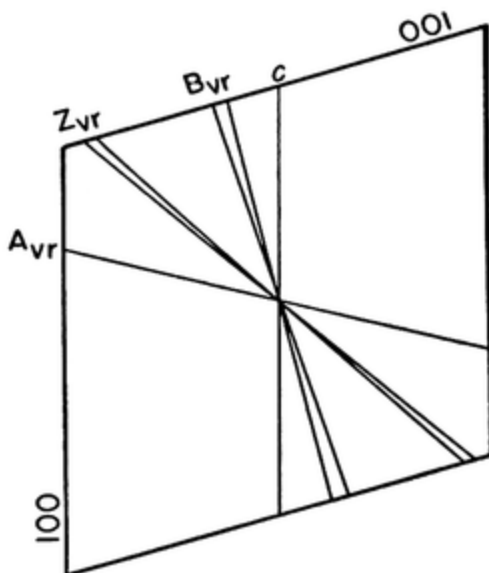


FIG. 301. Dispersion in ferroaugite from Renfrew, Canada.

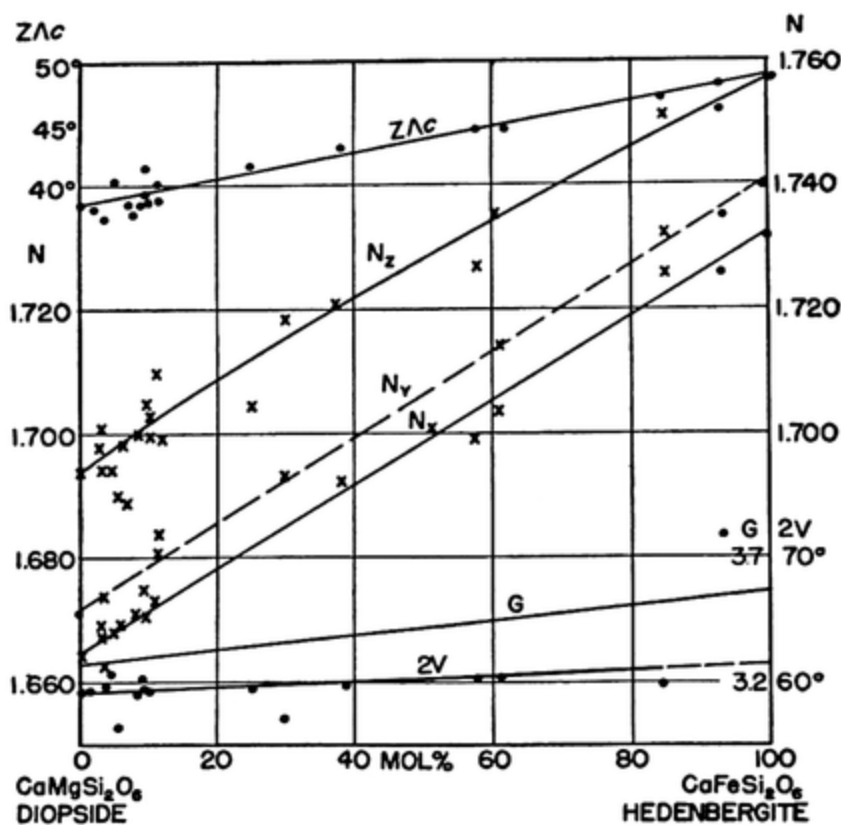


FIG. 302. Properties of the diopside-hedenbergite series.

$Z_r \wedge c > Z_v \wedge c$  in diopside and augite, and the reverse in ferroaugite and acmite (Fig. 301); in acmite this produces incomplete extinction in white light. The refringence ranges from about 1.67 in diopside to about 1.80 in acmite, being near 1.70 in common augite. The birefringence varies from about 0.012 for jadeite to about 0.06 for acmite, being

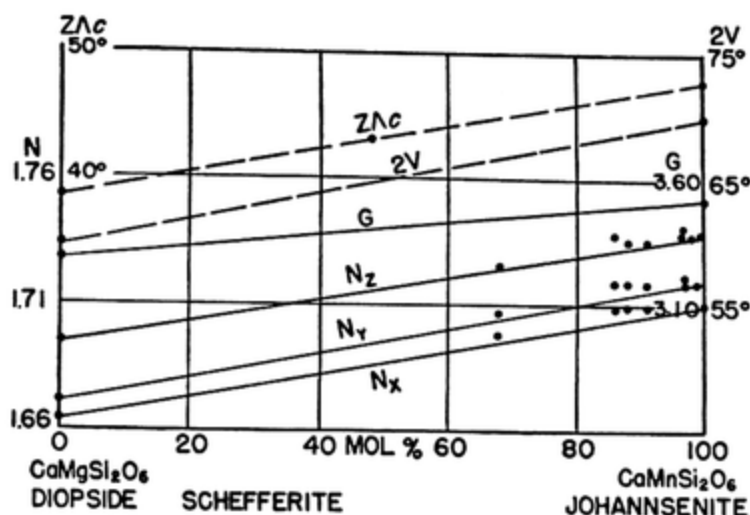


FIG. 303. Properties of the diopside-johannsenite series.

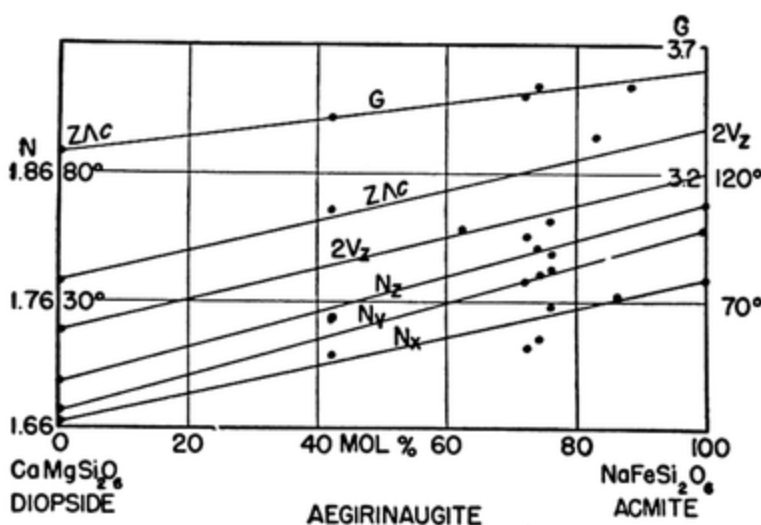


FIG. 304. Properties of the diopside-acmite series.

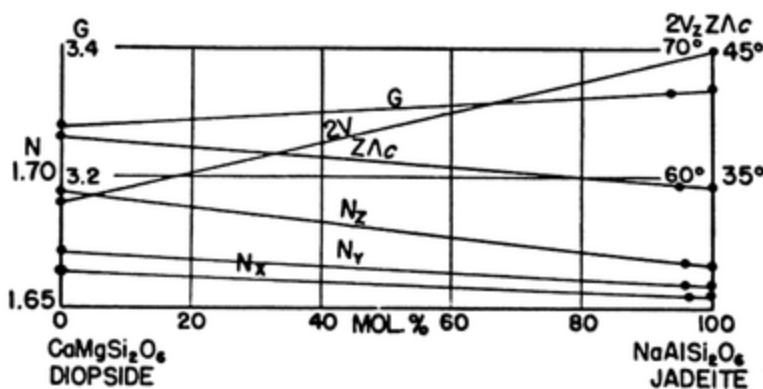


FIG. 305. Properties of the diopside-jadeite series.

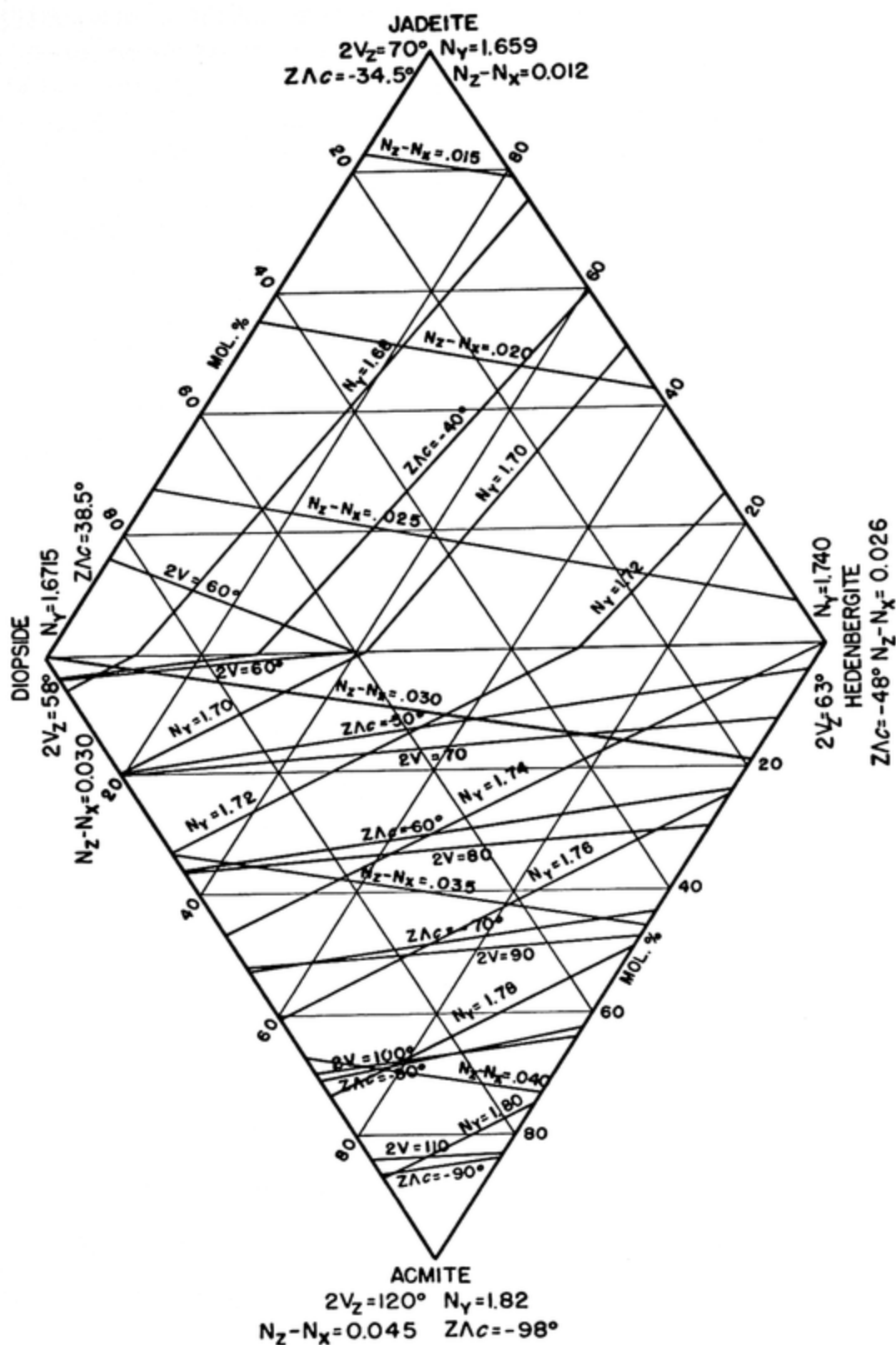


FIG. 306. Properties of the diopside-hedenbergite-acmite-jadeite systems. Based on scanty data.

about 0.025 for ordinary augite. The optic orientation of various types is shown in Figs. 296–300. The relations between variations in properties and in composition are shown in Figs. 302–306, and are illustrated in the following table:<sup>28</sup>

	2V <sub>Z</sub>	N <sub>X</sub>	N <sub>Y</sub>	N <sub>Z</sub>	N <sub>Z</sub> - N <sub>X</sub>	Z $\wedge$ c	G.
Diopside <sup>29</sup> (artificial)	58°	1.664	1.6715	1.694	0.030	38.5°	3.275
Salite <sup>30</sup> (10.6 FeO)	59°	1.692	1.699	1.721	0.029	43°	3.42
Ferrosalite <sup>31</sup> (18.1 FeO)	Large	1.704	1.714	1.735	0.031		
Hedenbergite <sup>32</sup> (22.9 FeO)		1.726	1.735	1.752	0.026	48°	
Mn-Hedenbergite <sup>33</sup> (9.5 MnO)	60°	1.710	1.720	1.736	0.026		3.46
Schefferite <sup>34</sup> (10. MnO)	60°	1.690	1.699	1.721	0.031	43°	
Jeffersonite <sup>34</sup> (8. ZnO)	74°	1.713	1.722	1.745	0.032	55°	
Johannsenite <sup>35</sup> (27.8 MnO)	70° ca.	1.710	1.719	1.738	0.028	48°	3.5 ca.
Augite <sup>36</sup> (4.6 FeO)	59°	1.687	1.694	1.713	0.026	41°	
Augite <sup>37</sup> (3. FeO)	58.5°	1.686	1.692	1.711	0.025	41.5°	3.34
Ferroaugite <sup>38</sup> (24.6 FeO)	49°	1.726	1.732	1.753	0.027	44°	3.48
Leucaugite <sup>39</sup> (0.8 FeO)	59°	1.678	1.685	1.703	0.025	40°	3.18
Titanaugite <sup>40</sup> (4.2 FeO)	51°	1.721	1.725	1.746	0.025	50°	3.40
Aegirinaugite <sup>41</sup> (3.7 FeO)	Large	1.720	?	1.747	0.027	66°	3.42
Acmite <sup>42</sup> (21.7 Fe <sub>2</sub> O <sub>3</sub> )	99° calc.	1.742	1.768	1.787	0.045		3.5
Acmite <sup>43</sup> (32.0 Fe <sub>2</sub> O <sub>3</sub> )	114°	1.762	1.799	1.814	0.052		
Acmite <sup>44</sup> (art.)	120°	1.776	1.816	1.836	0.060	98°	
Salite-acmite <sup>44</sup>	105° ca.	1.744	1.768	1.782	0.038	80°	3.55
Chloromelanite <sup>45</sup>	70°	1.653	?	1.685	0.032		3.4
Jadeite-acmite <sup>46</sup>		1.735		1.775	0.040	85°	
Diopside-jadeite <sup>47</sup>	75° ca.	1.666	1.674	1.688	0.022	45° ca.	
Jadeite <sup>47</sup>	70°	1.655	1.659	1.667	0.012	34.5°	3.335

<sup>28</sup> See also H. H. Hess: *Am. Mineral.*, XXXIV, 621 (1949).

<sup>29</sup> 90 CaMgSi<sub>2</sub>O<sub>6</sub> + 10 CaTiAl<sub>2</sub>O<sub>6</sub> has (+)2V = 60°, N<sub>X</sub> = 1.700, N<sub>Y</sub> = 1.708, N<sub>Z</sub> = 1.730 (T. F. W. Barth: *N. Jahrb. Min.*, Bl. Bd. LXIV, A, 217, 1931).

<sup>30</sup> H. von Eckerman: *Geol. För. Förh. Stockholm*, XLIV, 203 (1922).

<sup>31</sup> W. T. Schaller: *Am. Mineral.*, XIV, 319 (1929).

<sup>32</sup> N. L. Bowen *et al.*: *Am. Jour. Sci.*, CCXXVI, 260 (1933); indices in personal communication, Oct. 23, 1934.

<sup>33</sup> C. E. Tilley: *Mineral. Mag.*, XXVII, 236 (1946).

<sup>34</sup> C. Palache: *U. S. Geol. Surv. Prof. Paper* 180 (1935).

<sup>35</sup> W. T. Schaller: *Am. Mineral.*, XXIII, 575 (1938).

<sup>36</sup> J. E. Wolff: *Bull. Geol. Soc. Am.*, XLIX, 1619 (1938).

<sup>37</sup> R. Ohashi: *Mineral. Mag.*, XIX, 173 (1921).

<sup>38</sup> L. R. Wager and W. A. Deer: *Medd. Grøn.*, CV, No. 4 (1939).

<sup>39</sup> H. Ries: *Ann. N. Y. Acad. Sci.*, IX, 164 (1896).

<sup>40</sup> W. Wawryk: *Min. Abst.*, VI, 212 (1936). A uniaxial titanaugite is described by Dixon and Kennedy: *Zeit. Krist.*, LXXXVI, 112 (1933).

<sup>41</sup> E. S. Larsen and W. F. Hunt: *Am. Jour. Sci.*, CLXXXVI, 295 (1913). Contains 42.5% NaFeSi<sub>2</sub>O<sub>6</sub>.

<sup>42</sup> R. W. Goranson: *Am. Mineral.*, XII, 37 (1927). Contains 62.8% NaFeSi<sub>2</sub>O<sub>6</sub>.

<sup>43</sup> J. E. de Villiers: *Min. Abst.*, X, 125 (1947).

<sup>44</sup> H. S. Washington and H. E. Merwin: *Am. Mineral.*, XII, 233 (1927).

<sup>45</sup> P. L. Merritt: *Am. Mineral.*, XVII, 497 (1932).

<sup>46</sup> R. Doht and C. Hlawatsch: *Verh. Geol. Reich. Wien*, 1913, 79.

<sup>47</sup> H. S. Washington: *Proc. U. S. Nat. Mus.*, LX, Pt. 14 (1922), and *J. Wash. Acad. Sci.*, XII, 387 (1922).

The relations between composition and properties in the acmite-diopside series <sup>48</sup> (artificial) are like those of the natural series shown in Fig. 304.

Diopside is usually green in mass, but varies from colorless to greenish black; also brown; leucaugite is (nearly) colorless; common augite is green or brown to black, rarely grayish green or yellow; ferroaugite is usually darker; titanaugite is reddish or violet; hedenbergite is usually dark green; johannsenite is brown to black; *omphacite* is a green variety found in eclogites; aegirinaugite is dark green to black; acmite <sup>49</sup> is reddish brown or green to black; jadeite is apple to emerald green. In thin section diopside, leucaugite, common augite, and jadeite are colorless or nearly so; other types show pleochroism of various kinds, illustrated as follows:

	X	Y	Z
Ferrosalite	Greenish	Brownish or reddish	Greenish
Hedenbergite	Pale green	Yellowish green	Dark green
Ferroaugite	Greenish	Brownish or reddish	Greenish
Titanaugite	Greenish yellow or reddish	Red or violet	Greenish yellow, red- dish, or violet
Aegirinaugite	Olive or grass green	Green or yellow	Yellow or brownish
Acmite	Green or dark brown or pink	Green or clear brown or greenish blue	Yellow or brownish green or blue

INCL. Gaseous, liquid, and vitreous inclusions are sometimes arranged in zones. Some diallage has inclusions like those of bronzite giving a bronzy color and luster.

ALTER. Augite has many different alteration products; the commonest is probably *uralite* or secondary hornblende, a single crystal (or an aggregate) of which may replace a single crystal of pyroxene. The alteration may begin around the periphery, or it may proceed along cleavages. The green pyroxene of eclogite (called *omphacite*) alters similarly to a dark green hornblende called *smaragdite*. Another common alteration product is chlorite, with or without chrysotile, calcite, quartz, epidote, etc. Other alteration products include biotite, feldspar, talc, opal.

OCCUR. Diopside or common augite is an important constituent of many kinds of igneous rocks, such as gabbro, basalt, syenite, diorite.

<sup>48</sup> I. A. Ostrovsky: *Min. Abst.*, X, 464 (1949).

<sup>49</sup> Acmite may be yellow in thin section with little or no pleochroism, or may even be colorless, according to Washington and Merwin: *Am. Mineral.*, XII, 233 (1927).

See Fig. 307. Augite is especially abundant in igneous rocks, and diopside is common in contact rocks and schists, but neither is confined to such occurrences. Diopside and augite are found also in some meteorites and in certain types of slag. Hedenbergite is very rare, being found only in ore deposits and contact rocks. Johannsenite is still rarer in the same kinds of rocks. Aegirinaugite is not rare in nepheline syenite, phonolite, and other alkaline igneous rocks. Acmite is also found in such rocks. Jadeite occurs in certain metamorphic rocks. Prehistoric man used jadeite as well as nephrite in making images and certain utensils.

DIAG. Diopside grades into augite and is not easily distinguished from it by microscopical methods; however, it has less dispersion and therefore better extinction in white light than most augite. The birefringence of diopside is a little greater than that of most augite. Diopside differs from most clinoenstenite in the position of the optic plane and the size of the optic angle; it differs from acmite, jadeite, and spodumene in the size of the extinction angle. Augite has more dispersion than diopside, hedenbergite, or clinoenstenite, but this is not easily recognized, though it may prevent complete extinction in white light. Also,

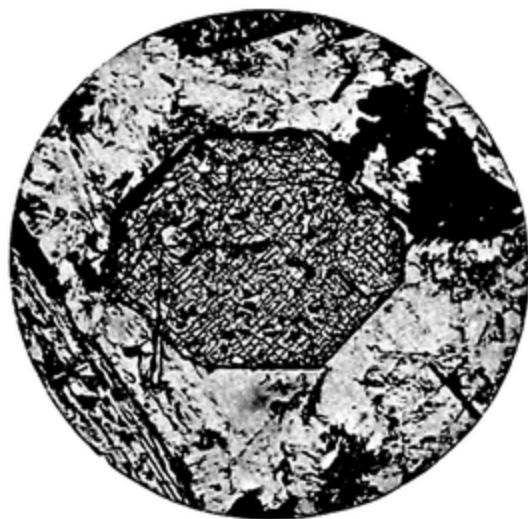


FIG. 307. Photomicrograph of augite in thin section.

the extinction angle in augite is usually greater (about  $45^\circ$ , also even up to  $54^\circ$ ) than in diopside ( $40^\circ$  ca.). Augite differs decidedly in extinction angle from aegirinaugite, acmite, and spodumene. Aegirinaugite is characterized by a large extinction angle ( $Z \wedge c$ ) and strong pleochroism. Acmite is characterized by its negative optic sign and negative sign of elongation with a small extinction angle ( $X \wedge c$ ); it also has strong birefringence. Jadeite is characterized by its fibrous habit and also differs from augite and diopside in its larger optic angle, smaller extinction angle, and mode of occurrence. Acmite and jadeite commonly contain 10 to 50 per cent of other pyroaugite end-members.

**SPODUMENE** (*Triphane*) MONOCLINIC PRISMATIC  $\text{LiAlSi}_2\text{O}_6$   
 $a:b:c = 1.144:1:0.632$   $\beta = 110^\circ 20'$

COMP. Like other pyroxenes spodumene can apparently take some  $\text{Al}_2\text{O}_3$  and  $\text{Fe}_2\text{O}_3$  in crystal solution, but it seems to have  $\text{HAlSi}_2\text{O}_6$



also, up to about 20 per cent. Small amounts of  $Na_2O$ ,  $MnO$ ,  $K_2O$  are found.<sup>50</sup>

STRUC. Space group <sup>27</sup>  $C2/c$ ;  $a$  9.50,  $b$  8.30,  $c$  5.24 Å.  
U.C. 4.

PHYS. CHAR. Crystals prismatic, often flattened on 100 and vertically striated. Twinning on 100. Distinct 110 cleavages at  $87^\circ$ ; parting on 010; rarely on 100.  $H. = 6-7$ .  $G. = 3.0-3.2$ .  $F.$  at  $1380^\circ$  after turning white, swelling, and giving a bright red flame color. Insoluble in acids.

OPT. PROP. The optic plane is parallel to 010; the bisectrix  $Z$  makes an angle with  $c$  of  $23^\circ$  to  $27^\circ$  in the obtuse angle  $\beta$ . See Fig. 308. Refringence and specific gravity seem to decrease with increase in tenor of  $AlSi_2O_6$ , but the data are not conclusive.

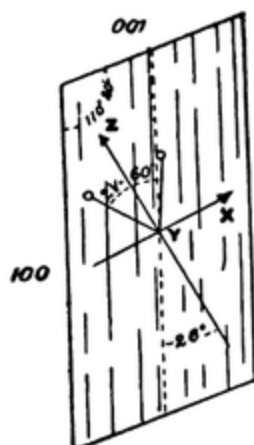


FIG. 308. The optic orientation of spodumene.

	Varu- trask <sup>51</sup>	Etta <sup>52</sup>	Etta <sup>52</sup>	Pitea <sup>53</sup>	India <sup>54</sup>	San Diego <sup>55</sup> Kunzite	North Carolina <sup>56</sup> Hiddenite
$LiAlSi_2O_6\%$	87.3	79.1	75.9	81.3	73.8	89.2	87.4
$(+ )2V = ?$	?	?	?	$66^\circ$	$58^\circ$	?	?
$N_X = 1.661$	1.656	1.648	1.653	1.653	1.653	1.652	1.651
$N_Y = 1.666$	1.660	1.655	1.659	1.667	1.667	?	1.669
$N_Z = 1.676$	1.672	1.662	1.677	1.678	1.678	1.679	1.677
$N_Z - N_X = 0.015$	0.016	0.014	0.024	0.025	0.025	0.027	0.026
$Z \wedge c = ?$	$23^\circ$	$24^\circ$	$25^\circ$	$26^\circ$	$26^\circ$	$25.5^\circ$	?
$G. = 3.13$	3.097	3.023	3.140	?	?	?	?

Color white, yellowish, greenish, emerald green (*hiddenite*), lilac (*kunzite*). Usually colorless in thin section and colorless to weakly pleochroic in thick plates, but deeply colored varieties are pleochroic as follows:

	X	Y	Z
Kunzite	Amethystine purple	Pink or amethystine	Colorless
Hiddenite <sup>57</sup>	Green	Greenish	Colorless

INVER. Spodumene <sup>58</sup> inverts at  $720^\circ$  to a tetragonal phase with a 30 per cent increase of volume; it has  $G. = 2.41$ ; it is uniaxial positive

<sup>50</sup> A. Gabriel, M. Slavin, and H. F. Carl: *Econ. Geol.*, XXXVII, 116 (1942).

<sup>51</sup> P. Quensel: *Geol. För. Förh. Stockholm*, LX, 201 (1938).

<sup>52</sup> G. M. Schwartz and R. J. Leonard: *Am. Jour. Sci.*, CCXI, 257 (1926).

<sup>53</sup> E. Grip: *Geol. För. Förh. Stockholm*, LXII, 380 (1941).

<sup>54</sup> B. R. Rao and M. B. Rao: *Min. Abst.*, VIII, 86 (1941).

<sup>55</sup> W. T. Schaller: *Univ. Calif. Dept. Geol. Bull.*, III, 265 (1903).

<sup>56</sup> A. Des Cloizeaux: *Am. Jour. Sci.*, CXXXII, 204 (1886).

<sup>57</sup> The pleochroic formula of hiddenite has been obtained by assuming that it has the same absorption formula as kunzite, namely,  $X > Y > Z$ .

<sup>58</sup> R. A. Hatch: *Am. Mineral.*, XXVIII, 471 (1943).

with  $N_O = 1.516-1.519$ ,  $N_E = 1.517-1.524$ ,  $N_E - N_O = 0.001-0.005$ .

**ALTER.** Spodumene may alter to a fibrous mass of eucryptite and albite.

**OCCUR.** It is found chiefly in pegmatite; also in gneiss. Rare.

**DIAG.** It differs from other monoclinic pyroxenes, except clinostatite, in the extinction angle, and from that in the position of the optic plane; it is also characterized by its mode of occurrence and the presence of much lithium.

## HYDROUS

**Juanite**<sup>59</sup> ( $\text{Ca}_{10}\text{Mg}_4\text{Si}_{11}\text{Al}_2\text{O}_{39} \cdot 4\text{H}_2\text{O}?$ ) is orthorhombic(?) in finely fibrous masses.  $H. = 5.5$ . Decomposed by acid. Positive sign of elongation and parallel extinction.  $(+)2V = 50^\circ(?)$ ,  $N_X = 1.640$ ,  $N_Y = ?$ ,  $N_Z = 1.647$ ,  $N_Z - N_X = 0.007$ . An alteration product of melilite at Iron Hill, Colorado.

**Bisbeeite** ( $\text{CuSiO}_3 \cdot \text{H}_2\text{O}$ ) is orthorhombic; crystals thin laths.  $H. = \text{soft}$ .  $X$  normal to laths and  $Z$  parallel to elongation.  $(+)2V = \text{small}$ ,  $N_X = 1.615$ ,  $N_Y = 1.625$ ,  $N_Z = 1.71$ ,  $N_Z - N_X = 0.095$ . Again  $N_X$  or  $N_Y = 1.59$ ,  $N_Z = 1.65$  (Schaller<sup>60</sup>). Color pale blue to nearly white and cottonlike. In thick section  $X$  and  $Y$  colorless to pale olive brown,  $Z$  colorless to pale green, and  $X$  and  $Y > Z$ . An alteration product of shattuckite in Arizona.

**Chrysocolla**<sup>61</sup> ( $\text{CuSiO}_3 \cdot 2\text{H}_2\text{O}$ ) is orthorhombic(?); very finely fibrous like chalcedony; conchoidal fracture; but it has a very distinctive X-ray pattern.  $H. = 2 \text{ ca.}$   $G. = 2.4 \text{ ca.}$   $F. = 7$ , but turns black. Attacked by acids. Reported as uniaxial positive with  $N_O = 1.46$ ,  $N_E = 1.54$ ,  $N_E - N_O = 0.08$  (Umpleby<sup>62</sup>); also as biaxial negative with  $N_X = 1.575$ ,  $N_Y = 1.597$ ,  $N_Z = 1.598$ ,  $N_Z - N_X = 0.023$ ; again  $N_X = 1.585$ ,  $N_Z = 1.635$ , the indices being apparently much lower until the pores are filled, according to Larsen.<sup>63</sup>  $\text{CuSiO}_3 \cdot 3\text{H}_2\text{O}$  has<sup>64</sup>  $G. = 3.08$ ,  $N = 1.51$ ,  $N_Z - N_X = \text{strong}$ . The data are very discordant (due to varying tenor of water or to presence of several minerals?). Color green, blue; also brown to black when impure with iron or copper oxides. Faintly pleochroic in some cases with  $X = \text{pale bluish green}$  and  $Z = \text{colorless}$ . Found in the oxide zone of copper deposits in siliceous rocks, as at Butte, Montana.

**Shilkinite**<sup>65</sup> ( $\text{H}_2\text{K}_2\text{Al}_6\text{Si}_8\text{Al}_2\text{O}_{30} \cdot 3\text{H}_2\text{O}?$ ) is orthorhombic(?).  $H. = 3-4$ .  $G. = 2.8$ . Distinct prismatic cleavage.  $Z$  parallel to elongation.  $(-)2V = 67^\circ$ ,  $r < v$ .  $N_X = 1.55$ ,  $N_Y = 1.570$ ,  $N_Z = 1.585$ ,  $N_Z - N_X = 0.035$ . Color green to

<sup>59</sup> E. S. Larsen and E. A. Goranson: *Am. Mineral.*, XVII, 343 (1932).

<sup>60</sup> W. T. Schaller: 3d App., *Dana's System Mineral.*, 14 (1915).

<sup>61</sup> An amorphous state of chrysocolla has been called *cornuite* by A. F. Rogers (*Jour. Geol.*, XXV, 515, 1917). It forms opaline coatings with  $H. = 2$ .  $G. = 2 \pm$ .  $F. = 7$ ; more soluble in  $\text{HCl}$  than crystalline chrysocolla. It has conchoidal fracture and is isotropic with  $N = 1.525-1.55$ . Color bluish green, blue; brown to black when impure.

<sup>62</sup> J. B. Umpleby: *U. S. Geol. Surv. Prof. Paper* 97, 51 (1917).  $N_O = 1.46$  and  $N_E = 1.57$ . See same author: *J. Wash. Acad. Sci.*, IV, 181 (1914).

<sup>63</sup> E. S. Larsen: *U. S. Geol. Surv. Bull.* 679 (1921) and 848 (1934).

<sup>64</sup> G. Carobbi: *Gazz. Chim. Ital.*, LVIII, 801 (1928).

<sup>65</sup> G. W. Merkulova: *Am. Mineral.*, XXVIII, 62 (1943).

white; weakly pleochroic with X = brownish yellow, Y = light yellow, Z = colorless. Found in pegmatite on the Shilka River, Transbaikial.

**Planchéite** ( $3CuSiO_3 \cdot H_2O$ ) is orthorhombic in fibrous masses. H. = 5.5. G. = 3.3. F. = 7. Difficultly attacked by HCl without gelatinization. X appears to be normal to a cleavage; Z is parallel to the elongation. (+)2V = medium,  $N_X = 1.730$ ,  $N_Y = ?$ ,  $N_Z = 1.811$ ,  $N_Z - N_X = 0.081$  (Schoep<sup>66</sup>).  $N_X = 1.66$  and  $1.67$ ,  $N_Z = 1.73$  (Gaubert<sup>67</sup>).  $N_Z = 1.70$  ca.  $N_Z - N_X = 0.04$  ca. (Lacroix<sup>16</sup>). May appear uniaxial, probably due to interwoven fibers; then  $N_X = 1.640$ ,  $N_Z = 1.697$ ,  $N_Z - N_X = 0.057$ . Isotropic fibers are also known with  $N = 1.678$ . Color pale to dark blue with X and Y = colorless, Z = blue. Said to vary in tenor of  $H_2O$  and therefore in indices. Found in copper ores in Africa.

**Shattuckite**<sup>68</sup> ( $2CuSiO_3 \cdot H_2O$ ) is monoclinic in fibrous masses which may be pseudomorphous after malachite. G. = 3.79. X = b; Z  $\wedge$  c (elongation) = small. (+)2V = large,  $N_X = 1.752$ ,  $N_Y = 1.782$ ,  $N_Z = 1.815$ ,  $N_Z - N_X = 0.063$  (Larsen<sup>63</sup>).  $N_X = 1.730$ ,  $N_Y = ?$ ,  $N_Z = 1.796$ ,  $N_Z - N_X = 0.066$  (Schaller<sup>68</sup>). Blue and strongly pleochroic with X and Y very pale blue, Z = blue to deep blue. Perhaps the same as *planchéite*.<sup>66</sup> Found with malachite at the Shattuck copper mine at Bisbee, Arizona.

**Crestmoreite** ( $2CaSiO_3 \cdot 3H_2O$ ) is monoclinic with 100(?) cleavage.<sup>69</sup> H. = 3. G. = 2.6. F. = easy. Decomposed by HCl. Z  $\wedge$  c (elongation)<sup>69</sup> = 12°. (-)2V = large,  $r > v$ .<sup>69</sup>  $N_X = 1.593$ ,  $N_Y = 1.603$ ,  $N_Z = 1.607$ ,  $N_Z - N_X = 0.014$  (Larsen<sup>63</sup>). Color snow white. Rare. *Riversideite* is a synonym.<sup>70</sup> *Jurupaite*<sup>71</sup> is probably a variety of crestmoreite<sup>72</sup> in which Mg proxies for part of the Ca. In it Z  $\wedge$  c = 31°, (+)2V = ?,  $N_X = 1.568$ ,  $N_Y = ?$ ,  $N_Z = 1.576$ ,  $N_Z - N_X = 0.007$ . Color white. Crestmoreite is found in veins in calcite and vesuvianite, at Crestmore, California.

**Searlesite** ( $NaBSi_2O_6 \cdot H_2O$ ) is monoclinic with  $a:b:c = 1.148:1:1.034$ ,  $\beta = 103^\circ 27'$ . Crystals prismatic with good 100 cleavage. H. = 3.5. G. = 2.45. F. = easy. Soluble in HCl. Chemically related to analcite. X  $\wedge$  c =  $30^\circ 15'$ , Z = b. (-)2V = moderate(?),  $N_X = 1.513$ ,  $N_Y = 1.533$ ,  $N_Z = 1.535$ ,  $N_Z - N_X = 0.022$  (Rogers<sup>73</sup>). (-)2V = very large,  $N_X = 1.520$ ,  $N_Y = ?$ ,  $N_Z = 1.528$ ,  $N_Z - N_X = 0.008$  (Larsen<sup>63</sup>).  $N_X = 1.525$ ,  $N_Y = 1.531$ ,  $N_Z = 1.535$ ,  $N_Z - N_X = 0.010$  (Fahey<sup>74</sup>). Color white. After several hours in cold dilute HCl  $N_Y = 1.465$ ,  $N_Z - N_X = 0.01$  and Z parallel to elongation. Found in samples from the Searles deep well in California.

**Inesite** [ $Ca_2Mn_7Si_{10}O_{28}(OH)_2 \cdot 5H_2O$ ] is triclinic pinacoidal with  $a:b:c = 0.970:1:1.321$ ,  $\alpha = 87^\circ 42'$ ,  $\beta = 132^\circ 35'$ ,  $\gamma = 97^\circ 1'$ . Space group<sup>75</sup>  $P1$ ;  $a$  8.89,  $b$  9.14,  $c$  12.14 Å. U.C. 1. Crystals prismatic to fibrous, radiated, with perfect 010 and good 100 cleavages. H. = 6. G. = 3.03. F. = 3. Decomposed by HCl. X

<sup>66</sup> A. Schoep: *Bull. Soc. Fr. Minéral.*, LIII, 375 (1930).

<sup>67</sup> P. Gaubert in H. Buttgenbach: *Mém. Acad. Belg. Sci.*, VII, fasc. 6 (1923).

<sup>68</sup> W. T. Schaller: *J. Wash. Acad. Sci.*, V, 7 (1915) and IX, 131 (1919); F. Zambonini: *C. R. Acad. Sci. Paris*, CLXVI, 495 (1918).

<sup>69</sup> E. E. Fairbanks: private communication, April 20, 1926.

<sup>70</sup> Flint, McMurdie, and Wells: *Jour. Res. Nat. Bur. Stand.*, XXI, 617 (1938).

<sup>71</sup> A. S. Eakle: *Am. Mineral.*, VI, 107 (1921).

<sup>72</sup> H. Berman: *Am. Mineral.*, XXII, 392 (1937).

<sup>73</sup> A. F. Rogers: *Am. Jour. Sci.*, CCVII, 498 (1924).

<sup>74</sup> J. J. Fahey: *Bull. Geol. Soc. Am.*, LVII, 1192 (1946).

<sup>75</sup> W. E. Richmond: *Am. Mineral.*, XXVII, 563 (1942).

nearly normal to 010;  $Z' \wedge c$  on 010 =  $60^\circ$  in acute angle  $\beta$ .  $Y' \wedge c$  on 100 =  $12^\circ$ – $15^\circ$  in obtuse angle  $\alpha$ .  $(- )2V = 74^\circ$ ,  $r > v$  strong.<sup>76</sup>  $N_X = 1.616$ ,  $N_Y = 1.641$ ,  $N_Z = 1.652$ ,  $N_Z - N_X = 0.036$ . Again:<sup>77</sup>  $N_X = 1.6185$ ,  $N_Y = 1.6395$ ,  $N_Z = 1.6498$ ,  $N_Z - N_X = 0.0313$ . Color rose to flesh red; weakly pleochroic. Found in manganese ores, as at Pajsberg, Sweden, and Quinault, Washington.

**Racewinite**<sup>78</sup> ( $H_2CaAl_{10}Si_{12}O_{36} \cdot 19H_2O?$ ) is massive with conchoidal fracture and no cleavage.  $H. = 2.5$ .  $G. = 1.94$ – $1.98$ .  $(- )2V =$  large,  $N_Y = 1.51$  ca.  $N_Z - N_X = 0.01$  ca. Color of fresh mineral in place underground is bluish green, changing slowly to yellow-brown and dark brown; in nitric acid the color becomes lighter brown; fragments which have been in nitric acid change color in clove oil to green. Found near porphyry in limestone at Bingham, Utah. Very rare.

**Spadaite**<sup>79</sup> ( $MgSiO_3 \cdot 2H_2O?$ ) is often apparently amorphous with  $H. = 2.5$ ,  $G. = 2.2$ ,  $F. = 4$ ; gelatinizes with HCl. Isotropic with  $N = 1.53$  ca. (Larsen<sup>63</sup>). Also platy with positive elongation<sup>79</sup> ( $Z \wedge c =$  nearly  $0^\circ$ ) and  $(+ )2V =$  small to medium,  $N_X = 1.521$ ,  $N_Y = 1.525$ ,  $N_Z = 1.545$ ,  $N_Z - N_X = 0.034$ . Refractive indices nearly the same<sup>79</sup> after heating to  $110^\circ$  and thus driving off half the water. Color reddish; luster pearly or greasy. Colorless in section. Found with wollastonite in lava; also in gold ore. Very rare.

**Neotocite**<sup>80</sup> ( $MnSiO_3 \cdot nH_2O?$ ) is apparently amorphous, but may be in part birefringent in rosettes.  $H. = 4$ .  $G. = 2.8$ .  $F. = 7$ . Attacked by acid. Isotropic with  $N = 1.53$ – $1.56$ ; also  $N = 1.49$ – $1.51$  ( $1.47$  ca.?). Color black, coal-like; brown in powder; reddish brown in section. Found in ore deposits.

## 2. Type formula $A_m(B_4X_{11})_n$ Double chains

### ANHYDROUS

#### AMPHIBOLE GROUP

The minerals of the amphibole group are orthorhombic and monoclinic metasilicates of magnesium, iron, and calcium, commonly with double silicates of sodium, aluminum, and ferric iron.

**PHYS. CHAR.** The crystals usually show decided vertical elongation and may be finely fibrous. They have well-developed prismatic cleavage at an angle of about  $124^\circ$ . Twinning on 100 is common and may be multiple. The specific gravity ranges from 2.9 to 3.55, and the hardness from 4 to 6.5. The minerals are fusible at 4 to 6, and insoluble, except slowly in HF.

**OPT. PROP.** The plane of the optic axes is parallel to 010 except in certain alkaline types, and in monoclinic amphiboles the axis  $Z$  makes

<sup>76</sup> J. J. Glass and W. T. Schaller: *Am. Mineral.*, XXIV, 26 (1939).

<sup>77</sup> C. O. Hutton: *Trans. Roy. Soc. New Zealand*, LXXI, 99 (1941).

<sup>78</sup> A. N. Winchell: *Econ. Geol.*, XIII, 611 (1918).

<sup>79</sup> W. T. Schaller and T. B. Nolan: *Am. Mineral.*, XVI, 231 (1931).

<sup>80</sup> J. T. Pardee, E. S. Larsen, and G. Steiger: *Jour. Wash. Acad. Sci.*, XI, 31 (1921).

an angle with the vertical axis of  $0^\circ$  to  $25^\circ$  in the obtuse angle  $\beta$ , with similar exceptions. These angles are shown in Fig. 309. The refringence and birefringence are lower than in corresponding pyroxenes and increase with increase in the tenor of iron. The birefringence of common types is about 0.020 to 0.025, but in grunerite and oxyhornblende it is

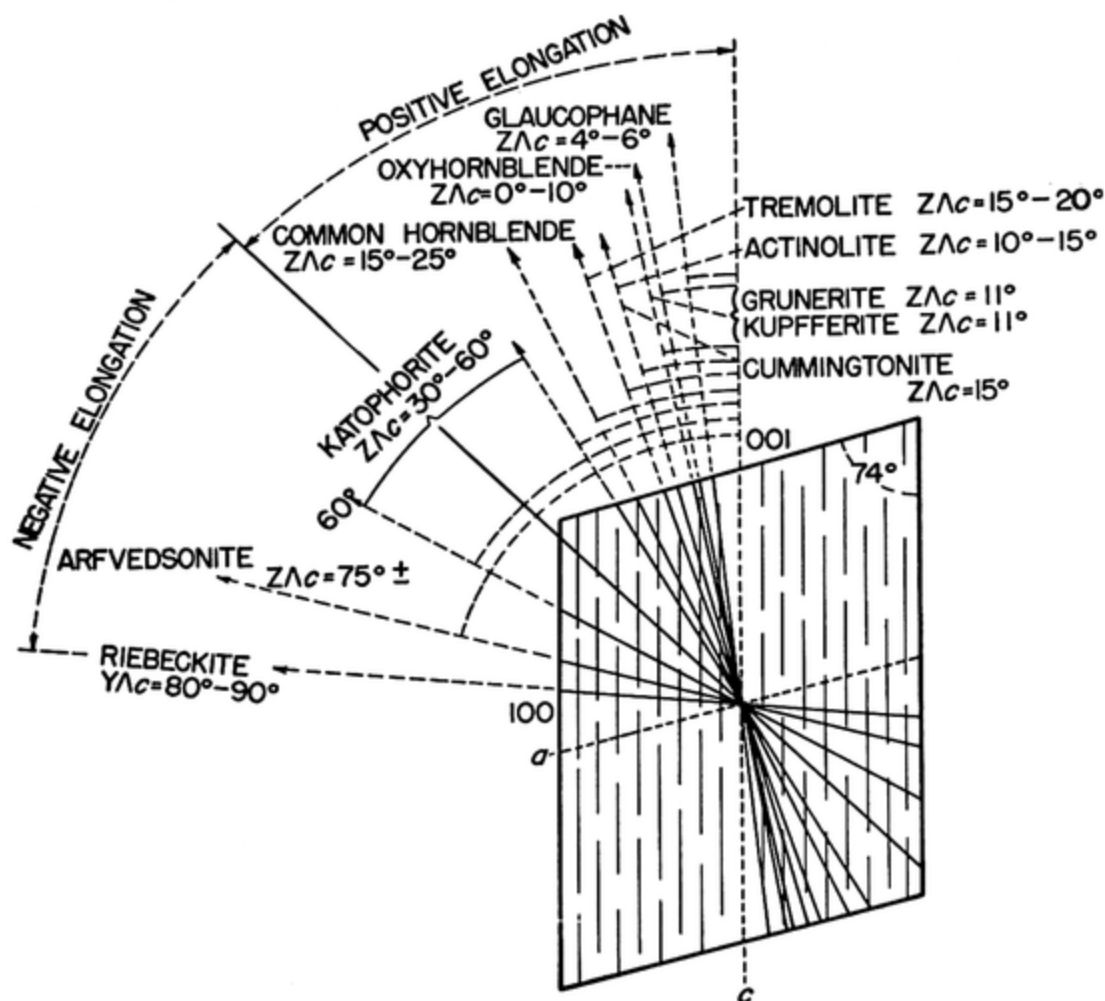


FIG. 309. Extinction angles of monoclinic amphiboles.

much more. Amphiboles in thin section are green, brown, yellow, blue, or colorless; pleochroism is usually distinct, and it is intense in the highly ferriferous types. In the common varieties absorption is greatest parallel to Z and least parallel to X.

**ALTER.** Amphiboles alter readily to chlorite, biotite, epidote, calcite, talc, etc. The alteration to chlorite, biotite, or talc is a gradual process, usually beginning along the edges and cleavages of the amphibole, and sometimes continuing until no trace of the original mineral, except

perhaps its form, is to be found. Under the action of intense heat, as, for instance, when fragments of amphibole crystals are caught in erupting magmas, the mineral is often rounded, corroded, and more or less fused. Upon cooling from such a fusion the amphibole does not recrystallize; in its place appear grains of magnetite, microlites of pyroxene, or an aggregate of these two minerals. Similarly, when amphiboles are artificially fused and then allowed to cool, the crystallized product is not amphibole but pyroxene, commonly with magnetite.

**OCCUR.** Amphiboles are found in nearly all classes of igneous rocks and in many metamorphic rocks. They may be sufficiently abundant to constitute rocks with other minerals so subordinate as to be merely accessories. Amphiboles are often formed by the alteration of pyroxenes.

**DIAG.** Amphiboles may be distinguished from pyroxenes thus:

Amphiboles	Pyroxenes
Cleavage angle about $124^{\circ}$ and $56^{\circ}$	Cleavage angle about $87^{\circ}$ and $93^{\circ}$
Crystals usually long prismatic	Crystals usually short prismatic
Color and pleochroism usually marked	Color and pleochroism usually weak
Maximum extinction angle in vertical zone $0^{\circ}$ – $25^{\circ}$ (except in certain alkaline types with unusual colors)	Maximum extinction angle in vertical zone $30^{\circ}$ – $54^{\circ}$ (except in certain alkaline types with unusual colors)
Most varieties optically negative	Most varieties optically positive
Alter to chlorite, etc. (change to pyroxene only through fusion)	Alter to amphibole, etc.

**CLASS.** The amphiboles are orthorhombic or monoclinic<sup>81</sup> in symmetry. Orthorhombic amphibole is called anthophyllite and it varies much in composition. Monoclinic amphibole is called hornblende, and it varies in composition in many ways, showing more variations than are known in any other mineral. The more important variations are shown on page 425.

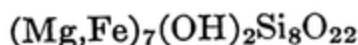
Continuous variation from cummingtonite to actinolite and common hornblende is very probable but has not yet been proved; it is therefore permissible to describe cummingtonite separately. All other kinds of hornblende probably belong to one continuous system but will be described in three groups, as a matter of convenience.

<sup>81</sup> Enigmatite and rhönite are commonly considered to be triclinic amphiboles, but they differ from amphiboles in composition and properties and are here considered by themselves.



SPECIES	SUBSPECIES	
Anthophyllite		$(Mg, Fe)_7(OH)_2Si_8O_{22}$
	Cummingtonite	$Mg_7(OH)_2Si_8O_{22}$
		$Fe_7(OH)_2Si_8O_{22}$
		$Ca_2Mg_5(OH)_2Si_8O_{22}$
		$Ca_2(Mg, Fe)_5(OH)_2Si_8O_{22}$
		$Ca_2Fe_5(OH)_2Si_8O_{22}$
		$Ca_2Mg_3Al_2(OH)_2Si_6Al_2O_{22}$
		$Ca_2Fe_3Al_2(OH)_2Si_6Al_2O_{22}$
		$NaCa_2Mg_5(OH)_2Si_7AlO_{22}$
		$NaCa_2Fe_5(OH)_2Si_7AlO_{22}$
		$NaCa_2Mg_4Al(OH)_2Si_6Al_2O_{22}$
		$NaCa_2Fe_4Al(OH)_2Si_6Al_2O_{22}$
		$Ca_2Fe''_3Fe'''_2O_2Si_8O_{22}$
		$Ca_2Fe''(Al, Fe''')_4O_2Si_6Al_2O_{22}$
		$NaCa_2Fe''_3Fe'''_2O_2Si_7AlO_{22}$
		$NaCa_2Fe''_2(Al, Fe''')_3O_2Si_6Al_2O_{22}$
		$Na_2Mg_3Al_2(OH)_2Si_8O_{22}$
		$Na_3Mg_3Al_2OOHSi_8O_{22}$
		$Na_2CaMg_3Al_2O_2Si_8O_{22}$
		$Na_2Fe''_3Fe'''_2(OH)_2Si_8O_{22}$
		$Na_3Fe''_4Fe'''(OH)_2Si_8O_{22}$
		$Na_3Mg_4(Al, Fe''')(OH, F)_2Si_8O_{22}$
		$Na_2Mg_3Al_2(OH)_2Si_8O_{22}$
		$Na_3Mg_3Al_2OOHSi_8O_{22}$
		$Na_2CaMg_3Al_2O_2Si_8O_{22}$
		$Na_2Fe''_3Fe'''_2(OH)_2Si_8O_{22}$
		$Na_3Fe''_4Fe'''(OH)_2Si_8O_{22}$
		$Na_3Mg_4(Al, Fe''')(OH, F)_2Si_8O_{22}$

## ANTHOPHYLLITE



ORTHORHOMBIC DIPYRAMIDAL

$$a:b:c = 0.967:1:0.285$$

COMP. Common anthophyllite is dominantly magnesian, but the variation extends from pure magnesian to at least about 60 mol. % of iron, and this series<sup>82</sup> is miscible (probably in all proportions) with  $(Mg, Fe)_5Al_2(OH)_2Si_6Al_2O_{22}$  (*gedrite*); further, Mg may be replaced in small part by Na, Mn, Ca, etc.

STRUC. Space group<sup>83</sup> *Pnma*;  $a$  18.5,  $b$  17.9,  $c$  5.27 Å. U.C. 4.

PHYS. CHAR. Crystals rare, usually fibrous. Perfect 110 cleavage<sup>83</sup> at  $125^\circ 37'$ .  $G. = 2.9-3.4+$ .  $H. = 5.5-6$ .  $F. = 4-6$ . Insoluble in acids.

OPT. PROP. The optic plane is parallel to 010 in all anthophyllites, with  $Z$  parallel to  $c$ , so that the elongation is positive; the optic sign is

<sup>82</sup> J. C. Rabbitt: *Am. Mineral.*, XXXIII, 263 (1948).

<sup>83</sup> B. E. Warren and D. I. Modell: *Zeit. Krist.*, LXXV, 161 (1930). These authors show the intimate structural relation between monoclinic and orthorhombic amphiboles, and between amphiboles and the corresponding pyroxenes. In both groups the cleavage of the orthorhombic members should be indexed 210, that of the monoclinic members, 110, because of a doubling of the length of the  $a$  axis.

variable, and the optic angle is usually large. See Fig. 310. Data follow (see Figs. 311 and 312):

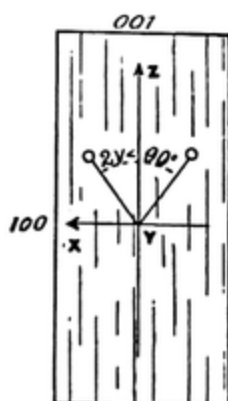


FIG. 310. The optic orientation of anthophyllite.

	Franklin <sup>84</sup>	Falun <sup>85</sup>	Mason Mt., N. C. <sup>86</sup>
Mol. % Fe	19.5	29.0	20.1
2V over X =	89°	114°	Large
$N_X$	1.6195	1.6329	1.642
$N_Y$	1.6301	1.6384	1.655
$N_Z$	1.6404	1.6517	1.661
$N_Z - N_X$	0.0209	0.0188	0.019
G.	3.09	3.157	3.178

Color brown, green, gray, white; streak colorless or gray; colorless in thin section, but may be pleochroic in thick section with X = brownish, Y = brownish, Z = yellow or pale green.

INCL. Gedrite often contains inclusions of biotite, spinel, zircon, rutile, etc.; it may contain inclusions like those giving name to bronzite.

ALTER. Anthophyllite alters rather easily to talc, bastite, etc.

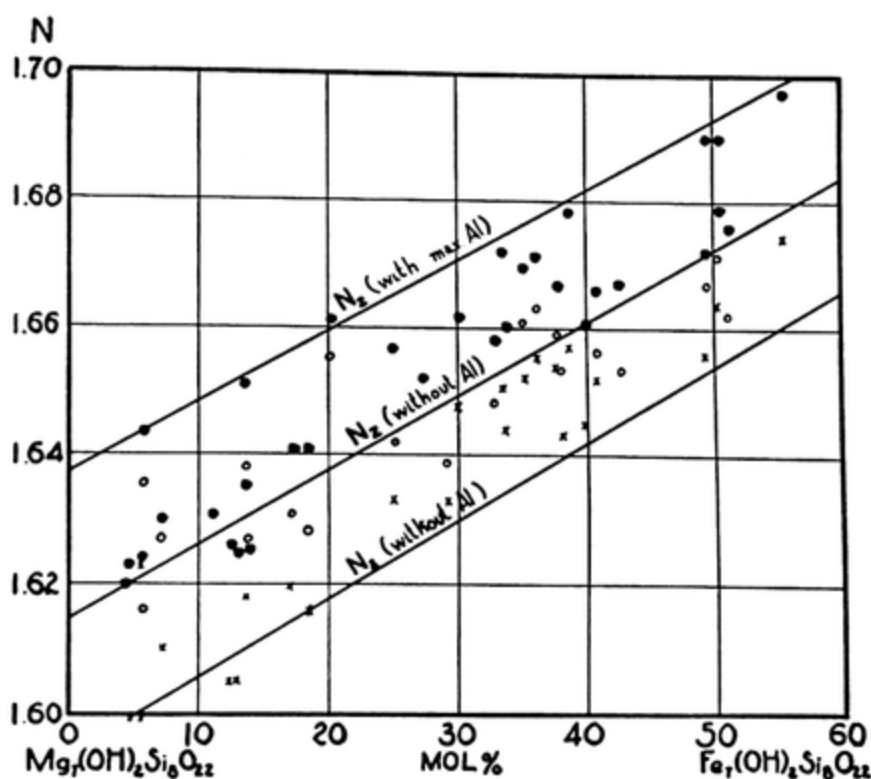


FIG. 311. Properties of anthophyllite.

<sup>84</sup> S. L. Penfield: *Am. Jour. Sci.*, CXL, 394 (1890), and N. L. Bowen: *J. Wash. Acad. Sci.*, X, 411 (1920).

<sup>85</sup> K. Johansson: *Zeit. Krist.*, LXXIII, 31 (1930).

<sup>86</sup> E. P. Henderson: *Am. Mineral.*, XVI, 563 (1931). Gedrite with 23.79  $Al_2O_3$ .

**OCCUR.** It is found in various schists and contact rocks; also, as a secondary mineral, in igneous rocks.

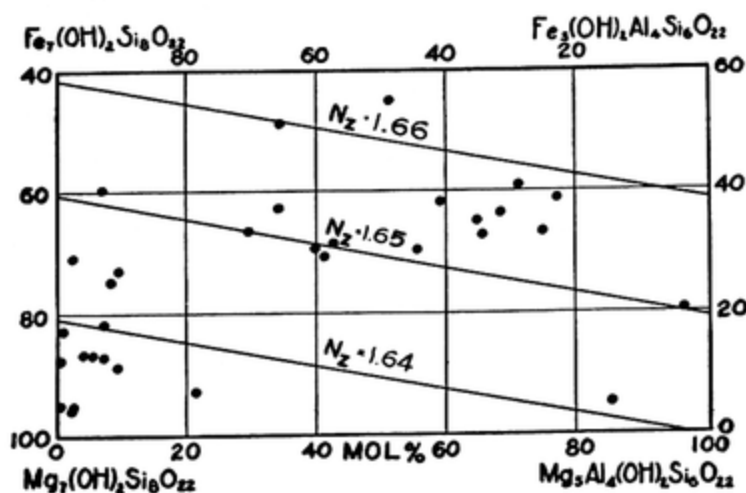


FIG. 312. Properties of anthophyllite (with Al).

**DIAG.** It is easily distinguished from monoclinic amphiboles by parallel extinction in vertical sections and lack of color.

**CUMMINGTONITE** MONOCLINIC PRISMATIC  $(Fe,Mg)_7(OH)_2Si_8O_{22}$   
 $a:b:c = 0.522:1:0.293$   $\beta = 106^\circ$

**COMP.** The magnesian end-member,  $Mg_7(OH)_2Si_8O_{22}$ , is called *kupferite*, and the iron end-member,  $Fe_7(OH)_2Si_8O_{22}$ , is called *grunerite*. Kupferite with less than about 25 mol. % of  $Fe_7Si_8O_{22}(OH)_2$  has not yet been found, and its properties have been derived by extrapolation. Small amounts of  $Al_2O_3$  and  $CaO$  are common in cummingtonite, and  $MnO$  may be present<sup>87</sup> at least to 14%, and  $ZnO$  to at least 10%.

**STRUC.** Space group<sup>88</sup>  $C2/m$ ;  $a$  9.7,  $b$  17.8,  $c$  5.25 Å for kupferite;  $a$  9.4,  $b$  17.9,  $c$  5.27 Å for grunerite. U.C. 4.

**PHYS. CHAR.** Crystals fibrous or lamellar with good 110 cleavages at  $125^\circ$ .  $G. = 3.2-3.5$ .  $F. = 5$  ca. to black magnetic glass. Insoluble in acids.

**OPT. PROP.** The optic plane is parallel to 010;  $Z \wedge c = -10^\circ$  to  $-20^\circ$ , passing a maximum at about 40 mol. % Fe (see Fig. 313). The optic angle varies from about  $75^\circ$

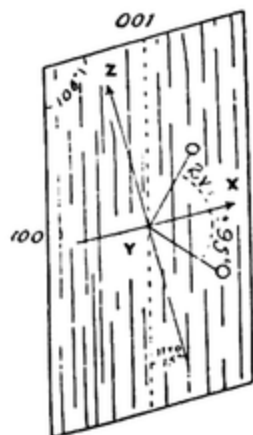


FIG. 313. The optic orientation of cummingtonite.

<sup>87</sup> L. H. Bauer and H. Berman: *Am. Mineral.*, XV, 340 (1930); Mn 27 mol. %; Zn 18 mol. %; Mg 29 mol. %.

<sup>88</sup> B. E. Warren: *Zeit. Krist.*, LXXII, 493 (1930).

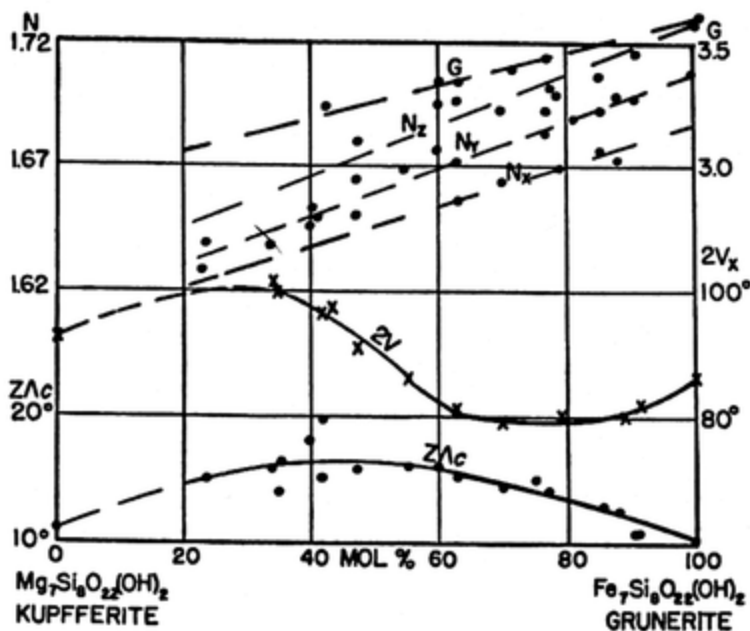


FIG. 314. Properties of the cummingtonite series.

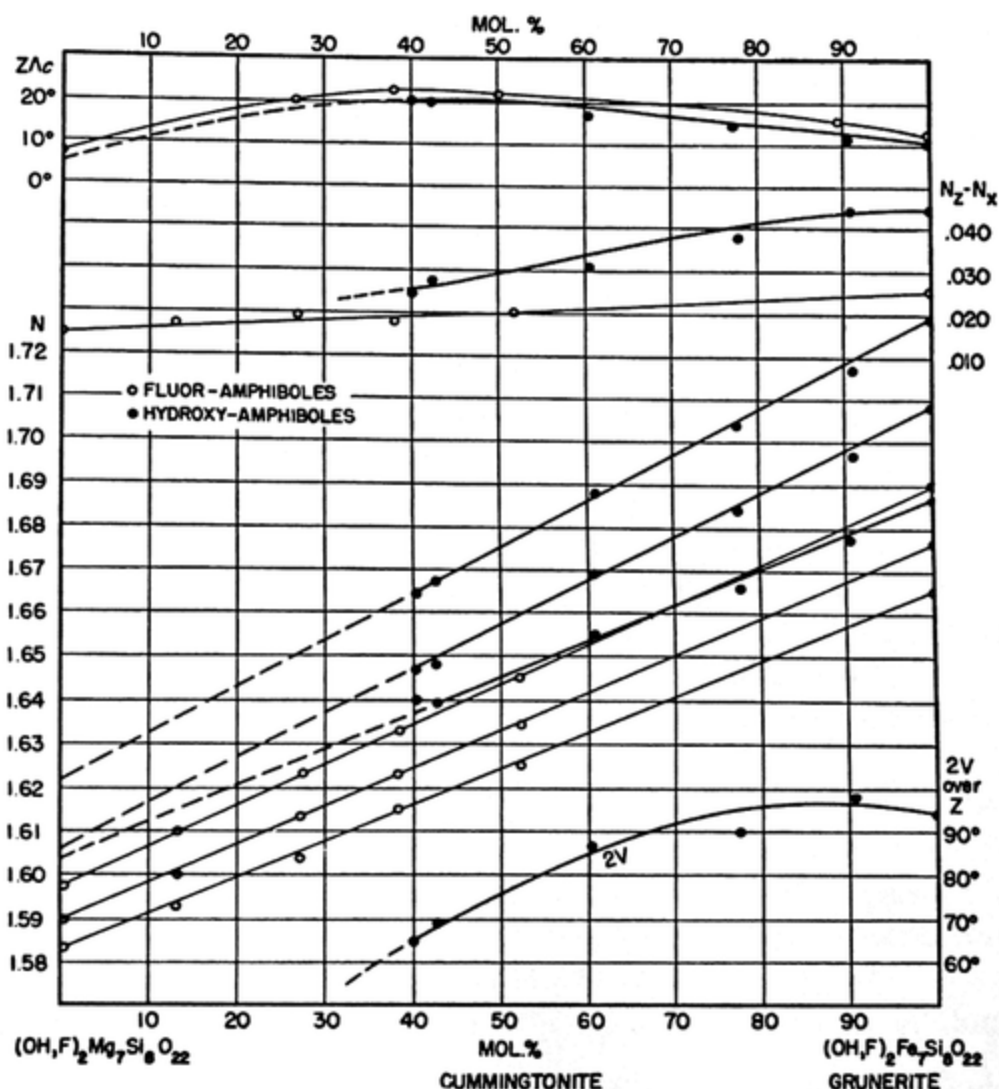


FIG. 315. Properties of fluorocummingtonite compared with hydroxycummingtonite. After N. L. Bowen and J. F. Schairer: *Am. Mineral.*, XX, 543 (1935).



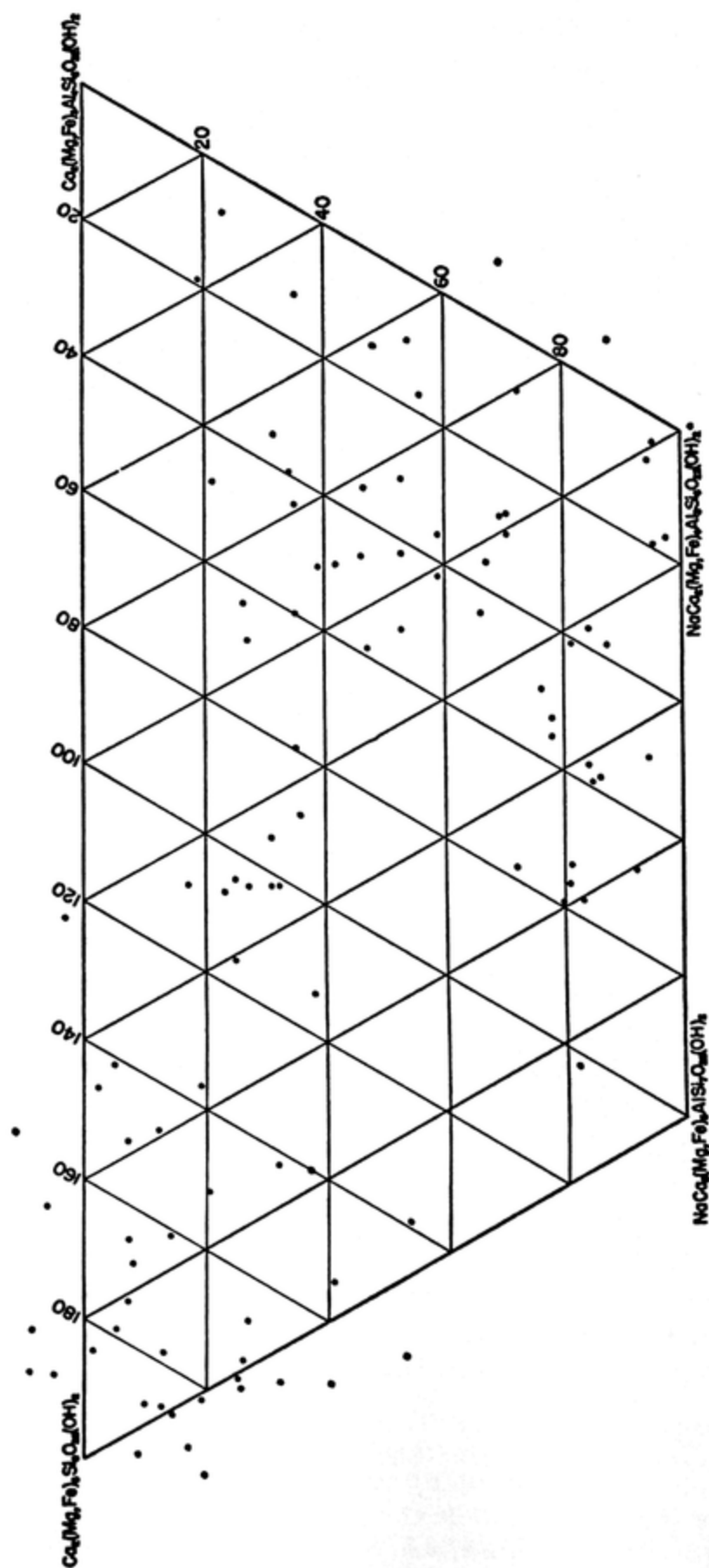


Fig. 317. Composition of calciferous hornblendes disregarding the Mg-Fe variation.



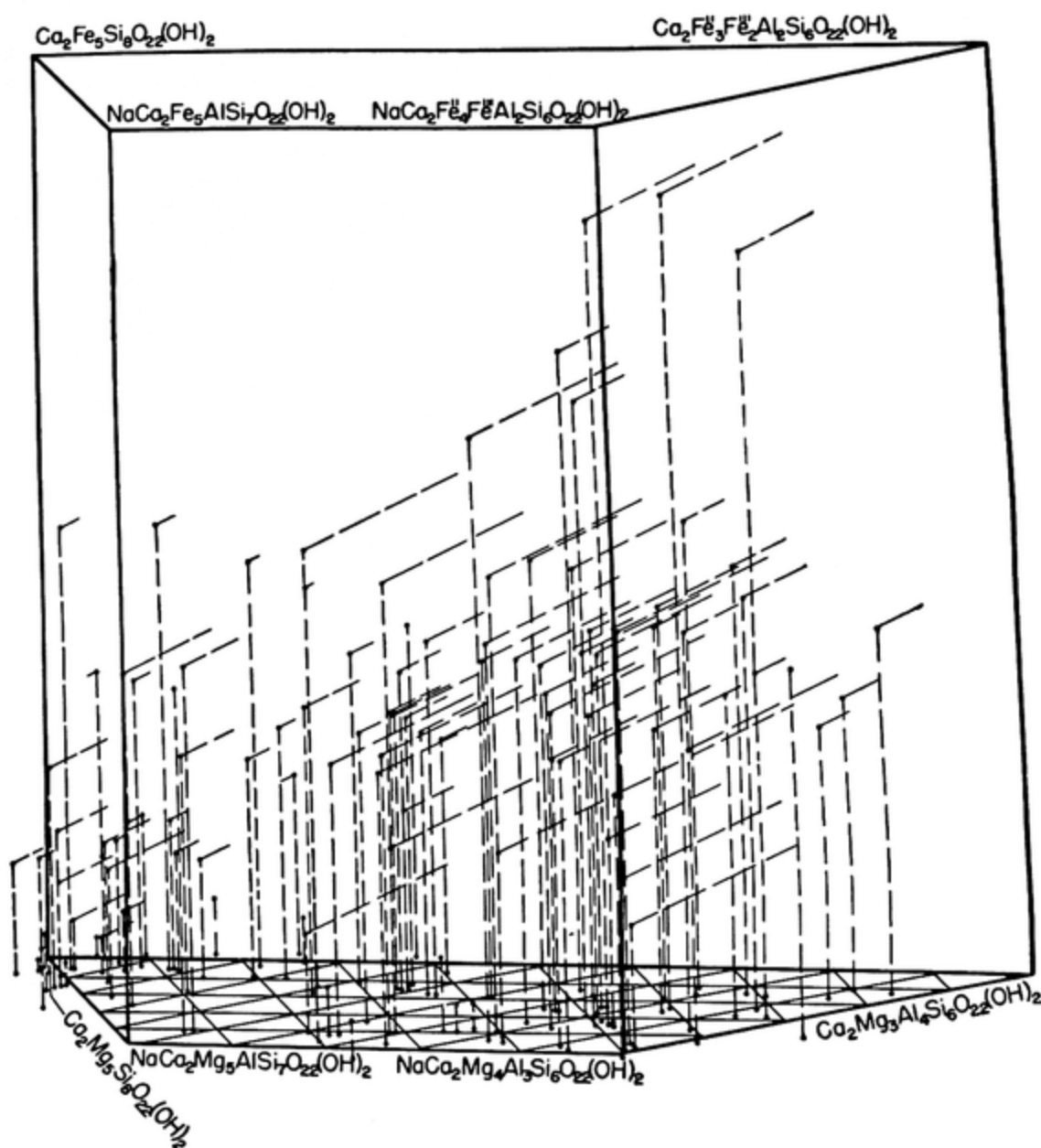
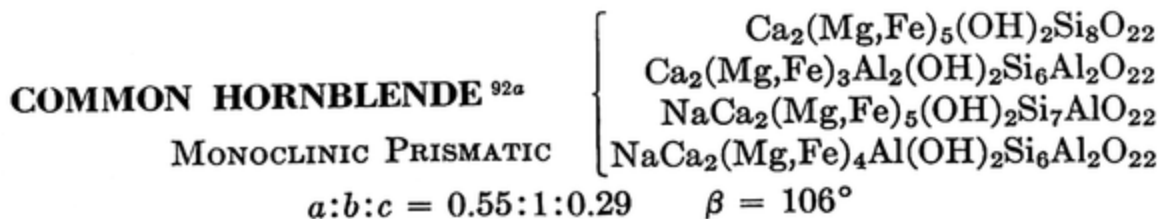


FIG. 318. Composition of calciferous hornblendes.



COMP. The formulas show the most important end-members, but there are many others, since F or Cl may proxy for OH, Mn or Ti for Fe'', Fe''' for Al, etc. Another variation is Na<sub>2</sub> for Ca (one Na atom occupying an otherwise vacant space in the crystal structure) leading to

<sup>92a</sup> Varieties are given in the table on page 425.

$\text{Na}_2\text{CaMg}_5(\text{OH})_2\text{Si}_8\text{O}_{22}$ , *richterite* or *soda-tremolite*. Samples having (almost) the composition of end-members are rare, except for tremolite,

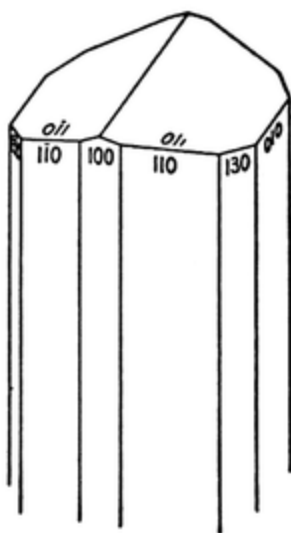


FIG. 319. A crystal form of common hornblende.



FIG. 320. Photomicrograph of hornblende in thin section.

$\text{Ca}_2\text{Mg}_5(\text{OH})_2\text{Si}_8\text{O}_{22}$ ; hornblende usually contains important percentages of several end-members. The chief variations in composition are shown diagrammatically in Figs. 317 and 318.

STRUC. Space group <sup>88</sup>  $C2/m$ ;  $a$  9.8,  $b$  17.9,  $c$  5.28 Å. U.C. 4.

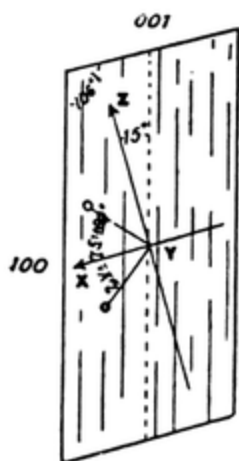


FIG. 321. The optic orientation of actinolite.

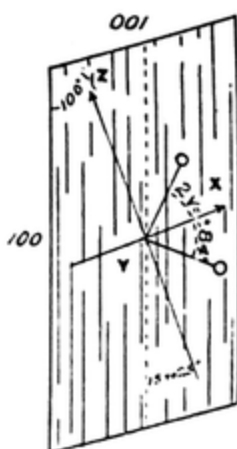


FIG. 322. The optic orientation of common hornblende.

PHYS. CHAR. Crystals usually long prismatic to acicular (see Fig. 319); also fibrous. Perfect 110 cleavages at  $124^\circ$  (see Fig. 320), also distinct 010 cleavage (or parting?). Parting on 100 or 001 accompanied by lamellar twinning.  $H. = 5-6$ .  $G. = 3.0-3.5$ , increasing with iron content. Insoluble in acid.

OPT. PROP. The optic plane is parallel with 010; the elongation is optically positive, and the extinction angle ( $Z \wedge c$  in obtuse angle  $\beta$ ) varies from about  $10^\circ$  to about  $30^\circ$ , being smallest in ferrotremolite and largest in hastingsite. See Figs. 321 and 322. The optic angle about  $X$  is about  $40^\circ$  in ferroedenite and ferrohastingsite and about  $130^\circ$  in

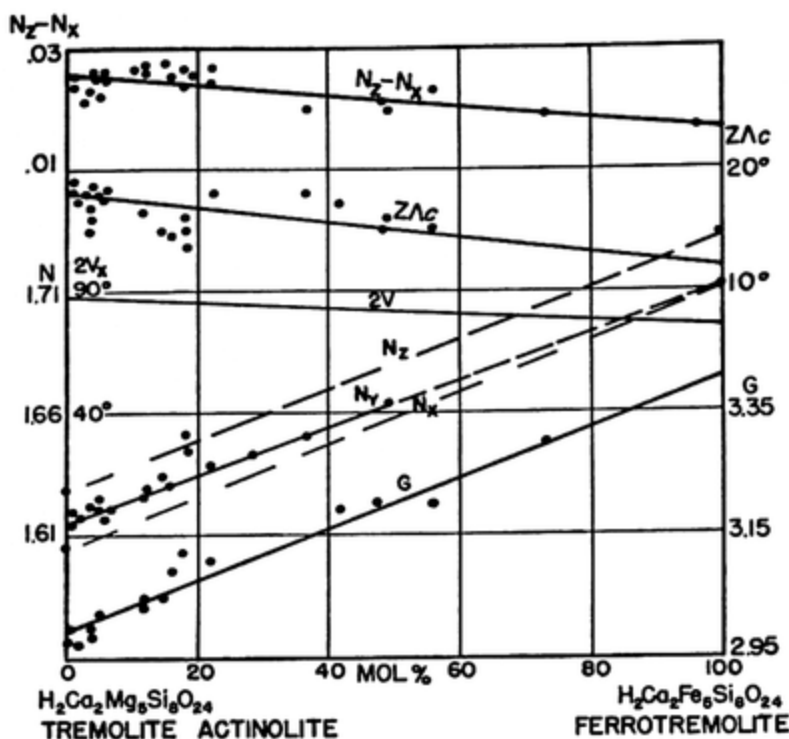


FIG. 323. Properties of the tremolite-ferrotremolite series.

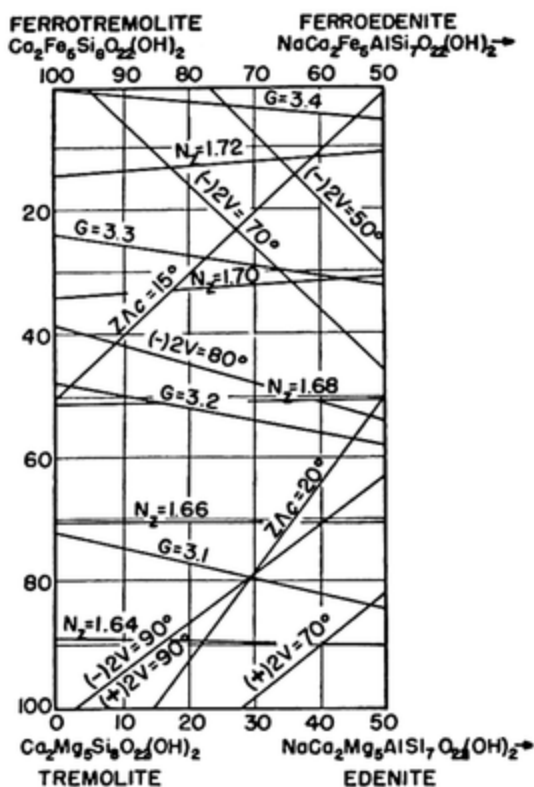


FIG. 324. Properties of the tremolite-edenite-ferrotremolite-ferroedenite system.

edenite.<sup>93</sup> The refringence ( $N_z$ ) ranges from about 1.63 in tremolite and edenite to about 1.75 in ferrotschermakite. The birefringence shows much less variation, ranging from about 0.02 to about 0.03. Dispersion is  $r < v$  in optically negative hornblende and  $r > v$  in pargasite.<sup>93</sup> Both

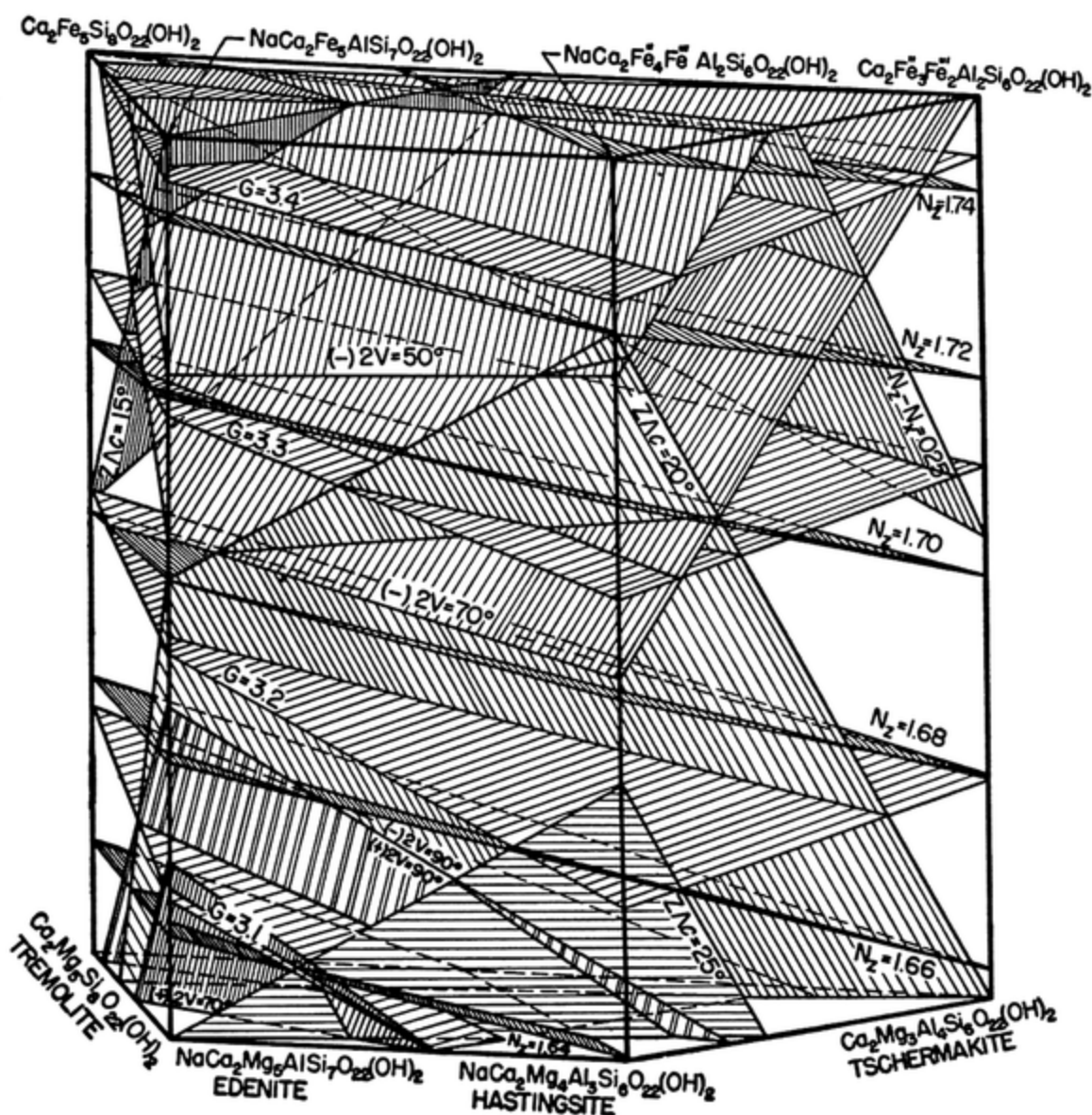


FIG. 325. Properties of the calciferous hornblende system.

have weak inclined dispersion. The relations between variations in composition and in properties are shown in Figs. 323–325 and illustrated in the following table giving the approximate properties<sup>94</sup> of end-members:

<sup>93</sup> Hornblende having a positive optic sign is usually called *pargasite*; it includes both edenite and hastingsite when they contain little iron.

<sup>94</sup> A. N. Winchell: *Am. Mineral.*, XXX, 27 (1945).

End-Member	Name	Sign 2V	N <sub>Z</sub>	N <sub>Z</sub> - N <sub>X</sub>	Z $\wedge$ c	G.
Ca <sub>2</sub> Mg <sub>5</sub> (OH) <sub>2</sub> Si <sub>8</sub> O <sub>22</sub>	Tremolite	-88°	1.628	0.03	18°	2.98
NaCa <sub>2</sub> Mg <sub>5</sub> (OH) <sub>2</sub> Si <sub>7</sub> AlO <sub>22</sub>	Edenite	+50°	1.63	0.02	25°	3.06
NaCa <sub>2</sub> Mg <sub>4</sub> Al(OH) <sub>2</sub> Si <sub>6</sub> Al <sub>2</sub> O <sub>22</sub>	Hastingsite	+85°	1.64	0.02	28°	3.15
Ca <sub>2</sub> Mg <sub>3</sub> Al <sub>2</sub> (OH) <sub>2</sub> Si <sub>6</sub> Al <sub>2</sub> O <sub>22</sub>	Tschermakite	-80°	1.657	0.02	20°	3.13
Ca <sub>2</sub> Fe <sub>6</sub> (OH) <sub>2</sub> Si <sub>8</sub> O <sub>22</sub>	Ferrotremolite	-75°	1.735	0.025	12°	3.40
NaCa <sub>2</sub> Fe <sub>5</sub> (OH) <sub>2</sub> Si <sub>7</sub> AlO <sub>22</sub>	Ferroedenite	-20°	1.73	0.02	15°	3.42
NaCa <sub>2</sub> Fe <sup>''</sup> <sub>4</sub> Fe <sup>'''</sup> (OH) <sub>2</sub> Si <sub>6</sub> Al <sub>2</sub> O <sub>22</sub>	Ferrohastingsite	-35°	1.74	0.02	18°	3.45
Ca <sub>2</sub> Fe <sup>''</sup> <sub>3</sub> Fe <sup>'''</sup> <sub>2</sub> (OH) <sub>2</sub> Si <sub>6</sub> Al <sub>2</sub> O <sub>22</sub>	Ferrotschermakite	-70°	1.75	0.03	18°	3.42

The following table gives the properties of various samples of hornblende:

Type	Locality	2V <sub>X</sub>	N <sub>X</sub>	N <sub>Y</sub>	N <sub>Z</sub>	N <sub>Z</sub> - N <sub>X</sub>	Z $\wedge$ c	G.
Tremolite <sup>95</sup>	Lee, Mass.	(-)88°	1.599	1.613	1.625	0.026	20°	2.98
Actinolite <sup>95</sup>	Greiner	(-)81.5°	1.618	1.633	1.641	0.023	15°	3.047
Pargasite <sup>96</sup>	Pargas	(+)63°	1.6329	1.6380	1.6519	0.019	26°	3.186
Edenite <sup>94</sup>	Franklin	(+)60°	1.622	1.630	1.645	0.023	27°	?
Hastingsite <sup>97</sup>	Pargas	(-)Large	1.622	1.632	1.641	0.019	18°-19°	3.163
Ferrohastingsite <sup>98</sup>	Idaho	(-)Small	1.693	1.710	1.713	0.020	17°	?
Ferrohastingsite <sup>99</sup>	Salmi	(-)Small	1.702		1.730	0.028	12°	3.447
Tschermakite <sup>100</sup>	Frankfort	(-)45°	1.680	1.695	1.698	0.018	22°	?
Hornblende <sup>100</sup>	Ottawa	(-)62°	1.6341	1.6472	1.6522	0.0181	21°	?
Hornblende <sup>101</sup>	Usumbura	(-)79°	1.650	1.665	1.675	0.025	19°	3.18
Hornblende <sup>102</sup>	Lindenfels	(-)66°	1.659	1.673	1.681	0.022	16.5°	3.234
Hornblende <sup>100</sup>	Renfrew	(-)38°	1.680	1.698	1.700	0.020	20°	?
Hornblende <sup>103</sup>	Mt. Monadnock	(-)43°	1.693	1.711	1.713	0.020	20°-21°	3.422

*Richterite* or *soda-tremolite*<sup>104</sup> [Na<sub>2</sub>CaMg<sub>5</sub>(OH)<sub>2</sub>Si<sub>8</sub>O<sub>22</sub>] is a type with Na<sub>2</sub> replacing Ca. With 45% soda-tremolite, 29% tremolite, and 22% glaucophane it has Z  $\wedge$  c = 24°, (-)2V = mod., N<sub>X</sub> = 1.606, N<sub>Y</sub> = 1.616, N<sub>Z</sub> = 1.623, N<sub>Z</sub> - N<sub>X</sub> = 0.017. With 8.69 MnO<sup>105</sup> it has Z  $\wedge$  c = 19°, (-)2V = 66° 30', N<sub>X</sub> = 1.622, N<sub>Y</sub> = 1.635, N<sub>Z</sub> = 1.641, N<sub>Z</sub> - N<sub>X</sub> = 0.019.

*Fluortremolite*<sup>106</sup> is a variety in which F proxies for OH; an artificial sample with 9.03 F has Z  $\wedge$  c = 23.5°, N<sub>X</sub> = 1.584, N<sub>Z</sub> = 1.606, N<sub>Z</sub> - N<sub>X</sub> = 0.022.

*Mangantremolite*<sup>107</sup> with Mn:Fe:Mg = 1:1.4:3.3 has (-)2V = 84°, N<sub>X</sub> = 1.637, N<sub>Y</sub> = 1.650, N<sub>Z</sub> = 1.660, N<sub>Z</sub> - N<sub>X</sub> = 0.023, Z  $\wedge$  c = 23°.

<sup>95</sup> S. L. Penfield and F. C. Stanley: *Am. Jour. Sci.*, CLXXIII, 23 (1907).

<sup>96</sup> A. Laitakari: *Bull. Com. Géol. Finlande*, 54, 55 (1921). Type 2.

<sup>97</sup> A. L. Parsons: *U. Toronto Geol. Stud.*, 29, 29 (1930), No. 5.

<sup>98</sup> M. Billings: *Am. Mineral.*, XIII, 287 (1928).

<sup>99</sup> T. G. Sahama: *Min. Abst.*, X, 269 (1948).

<sup>100</sup> V. E. Barnes: *Am. Mineral.*, XV, 393 (1930); A. N. Winchell: *Am. Mineral.*, XXX, 27 (1945).

<sup>101</sup> R. Van de Putte: *Bull. Mus. Hist. Nat. Belg.*, XV, No. 31 (1939).

<sup>102</sup> W. Kunitz: *N. Jahrb. Min.*, Bl. Bd. LX, A, 171 (1930).

<sup>103</sup> J. E. Wolff: *Jour. Geol.*, XXXVII, 1 (1929).

<sup>104</sup> E. S. Larsen: *U. S. Geol. Surv. Prof. Paper* 197A (1942).

<sup>105</sup> N. Sundius: *Sver. Geol. Und. Årsb.*, XL, No. 4 (1946).

<sup>106</sup> D. P. Grigoriev: *C. R. Acad. Sci. U.R.S.S.*, XXIII, 71 (1939); *Min. Abst.*, VII, 477 (1940).

<sup>107</sup> T. Yosimura: *Jour. Fac. Sc. Hokkaido U.*, IV, 3-4, 313 (1939); *Am. Mineral.*, XXIV, 659 (1939).

*Dashkessanite*<sup>108</sup> is hornblende in which Cl proxies for OH; a sample with 7.24 Cl, 19.99 FeO, 7.60 Fe<sub>2</sub>O<sub>3</sub>, has  $G. = 3.59$ ,  $(- )2V = 15^{\circ} \text{ ca.}$ ,  $N_X = 1.728$ ,  $N_{Z'} = 1.751$ ,  $Z \wedge c = 11^{\circ}$ .

Hornblende is colorless or nearly so when it contains little, if any, iron; tremolite, pargasite, and edenite are usually colorless. Hornblende is nearly always dark green or brown in mass and pleochroic in green, brown, or yellow tints. Examples follow:

	X	Y	Z
Actinolite	Very pale yellow	Greenish yellow	Pale to dark green
Pargasite	Greenish yellow	Emerald green	Greenish blue
Ferrohastingsite	Smoky blue-green	Brownish green	Greenish brown
Hornblende	Light green	Dark green	Very dark green
Hornblende	Light bluish green	Deep green	Deep bluish green
Hornblende	Light green	Yellowish green	Bluish green
Edenite	Colorless	Light violet-blue	Light violet-blue
Hornblende	Pale yellow	Brownish yellow	Reddish yellow
Hornblende	Clear yellow	Dark brown	Dark brownish green
Hornblende	Greenish brown	Reddish brown	Red-brown

**INCL.** Inclusions are common, such as apatite, zircon, magnetite, etc., but none is characteristic. Carbonaceous matter or biotite is occasionally found in actinolite. Vitreous inclusions occur in hornblende of some volcanic rocks; rutile is common in hornblende of metamorphic rocks.

**ALTER.** Hornblende usually alters to chlorite, sometimes with epidote, calcite, siderite, quartz, etc. Tremolite and actinolite may alter to talc. Less commonly hornblende alters to biotite with or without epidote; rarely it may change to titanite. By loss of hydrogen (due to high temperature) it may change to oxyhornblende.

**OCCUR.** Tremolite and actinolite are found chiefly in schists and contact rocks; also in veins, and as alteration products in igneous rocks. Pargasite is found especially in contact zones but also in igneous rocks. Hornblende is important in igneous rocks, and especially abundant in diorite; it is also found in some schists and contact rocks.

**Varieties.** *Asbestus* of commerce is a fibrous mineral which may be a variety of tremolite, actinolite, riebeckite, anthophyllite, or chrysotile; some of the best is the last type. *Jade* is a tough, compactly interlaced mineral, white to dark green in color, used ever since the times of early man for ornaments; it is often *nephrite*, a variety of tremolite or actinolite; sometimes it is a variety of *jadeite*, one of the pyroxenes. *Uralite* is a name given to amphibole which is produced by the alteration of

<sup>108</sup> G. A. Krutov: *Bull. Acad. Sci. U.R.S.S. Geol.*, 371, 1936; *Min. Abst.*, VI, 438 (1937).



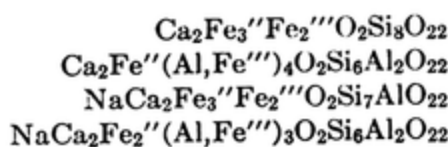
pyroxene; it is usually actinolite, but may be tremolite or hornblende.

**DIAG.** Hornblende with little or no iron, like tremolite and some edenite, differs from ordinary hornblende in its lack of color. Tremolite and iron-free edenite also have exceptionally low indices of refraction as compared with other hornblendes. All amphiboles differ from pyroxenes in their ( $124^\circ$ ) cleavage angle. Pargasite differs from all other hornblendes in having a positive optic sign. All common hornblendes have moderate to high relief and similar birefringence; they have marked vertical elongation of positive sign and maximum extinction angles of  $15^\circ$  to  $25^\circ$ . Most hornblende has distinct green to brown color and pleochroism.

### OXYHORNLENDE<sup>109</sup> MONOCLINIC PRISMATIC

$$a:b:c = 0.546:1:0.293 \quad \beta = 104^\circ 45'$$

Ferritremolite  
Ferritschermakite  
Ferriedenite  
Ferrihastingsite



**COMP.** Any type of common hornblende containing iron can be oxidized to the maximum extent indicated by the formulas given above. Titaniferous oxyhornblende has been called *kaersutite*.

**STRUC.**<sup>110</sup>  $a$  9.88,  $b$  18.10,  $c$  5.31 Å. U.C. 4.

**PHYS. CHAR.** Crystals long prismatic with good 110 cleavages at  $124^\circ$ .  $H. = 5-6$ .  $G. = 3.2-3.5$ , increasing with iron content.

**OPT. PROP.** The optic plane is parallel with 010;  $Z \wedge c = 0^\circ-15^\circ$  (usually very small). See Fig. 326. Both the refringence and the birefringence of oxyhornblendes are greater than those of corresponding common hornblendes. The relations between variations in composition and in properties are shown in Figs. 327 and 328; approximate properties of the iron end-members of the system are given in the following table:

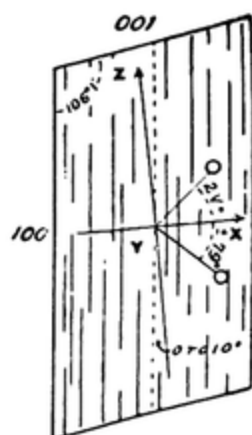


FIG. 326. The optic orientation of oxyhornblende.

End-Member	Sign	2V	$N_z$	$N_z - N_x$	$Z \wedge c$
$\text{Ca}_2\text{Fe}_3''\text{Fe}_2'''\text{O}_2\text{Si}_8\text{O}_{22}$	—	$55^\circ$	1.78	0.070	$0^\circ$
$\text{Ca}_2\text{Fe}''\text{Fe}_4'''\text{O}_2\text{Si}_6\text{Al}_2\text{O}_{22}$	—	$55^\circ$	1.80	0.095	$0^\circ$
$\text{NaCa}_2\text{Fe}_3''\text{Fe}_2'''\text{O}_2\text{Si}_7\text{AlO}_{22}$	—	$60^\circ$	1.79	0.075	$0^\circ$
$\text{NaCa}_2\text{Fe}_2''\text{Fe}_3'''\text{O}_2\text{Si}_6\text{Al}_2\text{O}_{22}$	—	$55^\circ$	1.80	0.085	$0^\circ$

<sup>109</sup> Often called *basaltic hornblende*; called *lamprobolite* by A. F. Rogers: *Am. Mineral.*, XXV, 826 (1940).

<sup>110</sup> B. Gossner and F. Spielberger: *Zeit. Krist.*, LXXII, 111 (1929).

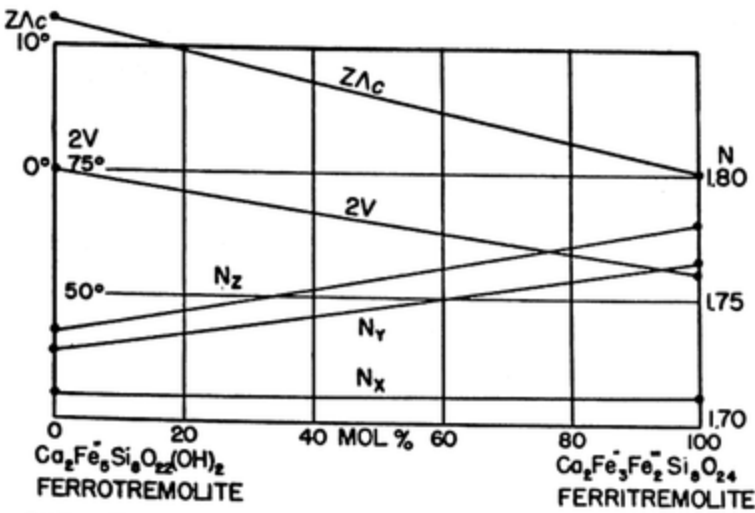


FIG. 327. Properties of the ferrotremolite-ferritremolite series.

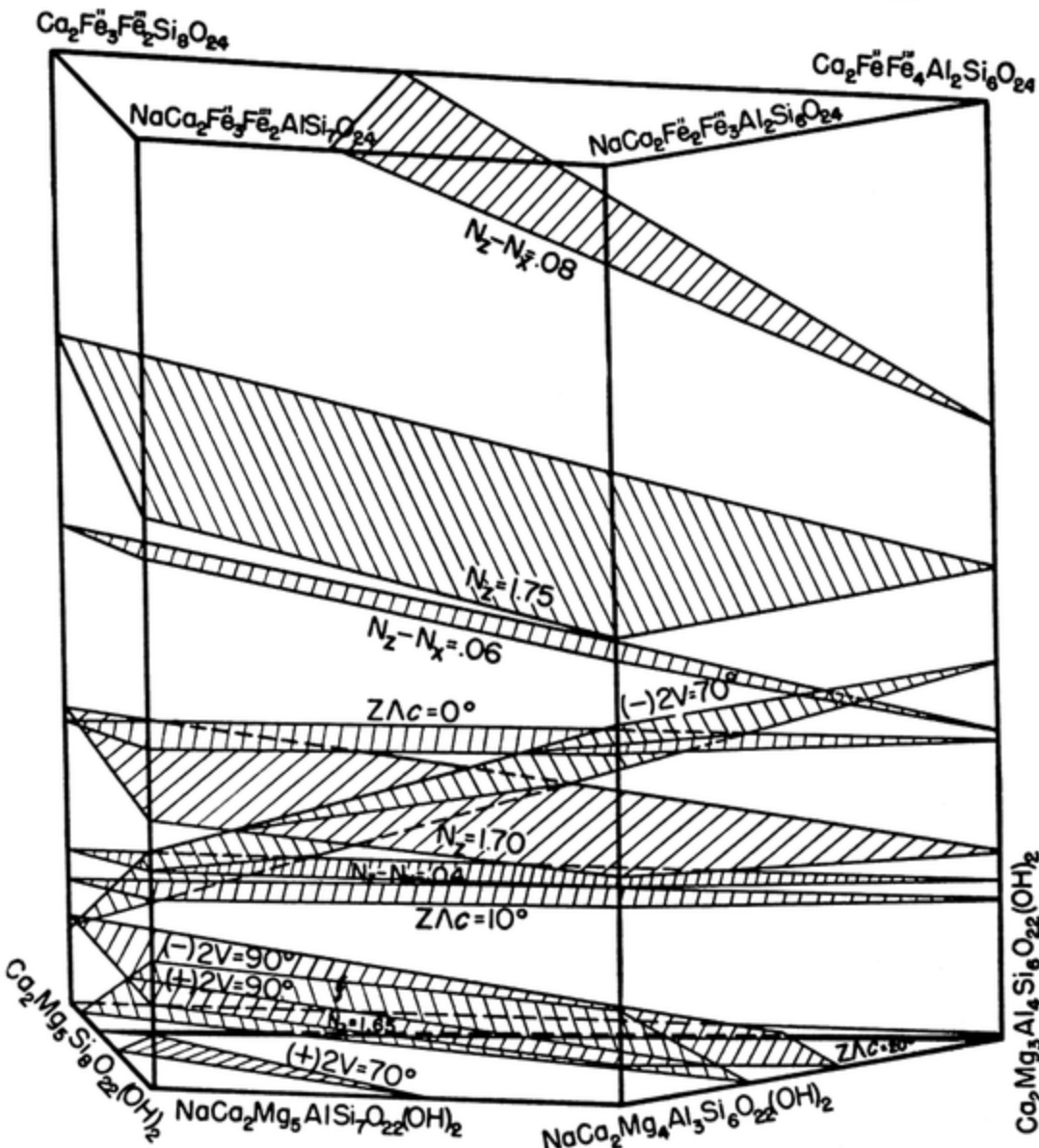


FIG. 328. Properties of calciferous oxyhornblendes.

The following table gives the properties of a few samples of oxyhornblende:

Type	Locality	$2V_X$	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$	$Z \wedge c$
Oxyhornblende <sup>111</sup>	Dry Gulch	(-)Lg.	1.675	1.715	1.735	0.060	5°
Oxyhornblende <sup>112</sup>	Ottawa	(-)56°	1.650	1.698	1.711	0.061	0°
Oxyhornblende <sup>112</sup>	Renfrew Co.	(-)65°	1.702	1.769	1.796	0.094	0°
Kaersutite <sup>113</sup>	Linosa	(-)80°	1.692	1.730	1.760	0.068	1.5°

Oxyhornblende is usually dark brown, but the pleochroic colors vary, for example:

Type	X	Y	Z
Oxyhornblende	Greenish yellow	Brownish green	Dark blue
Oxyhornblende	Pale yellow	Dark brown	Dark olive green
Oxyhornblende	Pale brown or yellow	Dark brown	Dark brown
Kaersutite	Light brown	Dark reddish brown	Dark reddish brown

Natural oxyhornblendes are usually oxidized only partially, rather than completely. Therefore their properties are intermediate between those of ordinary hornblende and those of completely oxidized hornblende. The size of the extinction angle is an approximate guide to the amount of oxidation, but natural oxyhornblendes with an extinction angle of 0° are not completely oxidized, at least in most cases.

**OCCUR.** Oxyhornblende is found in volcanic rocks such as basalt under conditions which suggest that it was formed, not as a primary mineral, but as an alteration product of common hornblende. The alteration involves no introduction of oxygen, but only loss of hydrogen.

**DIAG.** Oxyhornblende is characterized by high refringence, very strong birefringence, dark brown color, pleochroism, and small extinction angle.

#### SODA-HORNBLENDE MONOCLINIC PRISMATIC

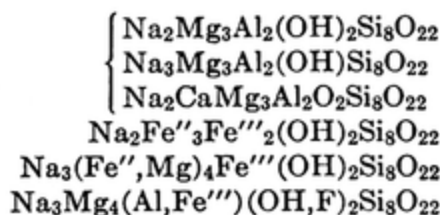
$$a:b:c = 0.54:1:0.29 \quad \beta = 105^\circ \text{ ca.}$$

##### Glaucophane

##### Riebeckite

##### Arfvedsonite

##### Eckermannite



<sup>111</sup> E. S. Larsen *et al.*: *Am. Mineral.*, XXII, 889 (1937).

<sup>112</sup> V. E. Barnes: *Am. Mineral.*, XV, 393 (1930).

<sup>113</sup> H. S. Washington and F. E. Wright: *Am. Jour. Sci.*, CLXXVI, 187 (1908).

With 8.5%  $\text{TiO}_2$ .



The vertical elongation is negative in arfvedsonite and riebeckite, variable in eckermannite, and positive in glaucophane. The extinction angle ( $X \wedge c$ ) ranges from  $+5^\circ$  to  $+45^\circ$  in arfvedsonite,<sup>117</sup> from  $25^\circ$  to  $53^\circ$  in eckermannite, from  $0^\circ$  to  $+5^\circ$  in

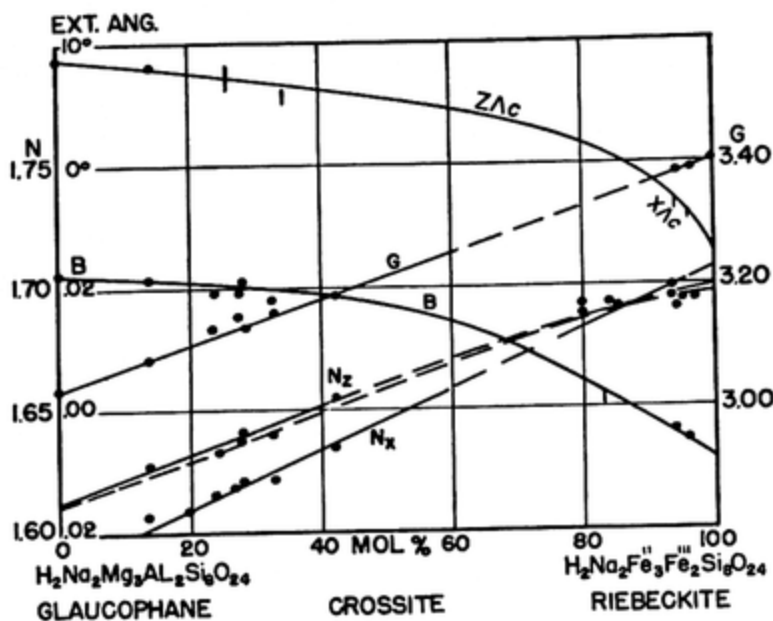


FIG. 334. Properties of the glaucophane-riebeckite series.

the acute angle  $\beta$  in riebeckite; the angle  $Z \wedge c$  varies from very small to at least  $-8^\circ$  in glaucophane. Strong dispersion of the bisectrices causes incomplete extinction in white light in arfvedsonite and crossite. The optic sign is negative except in some

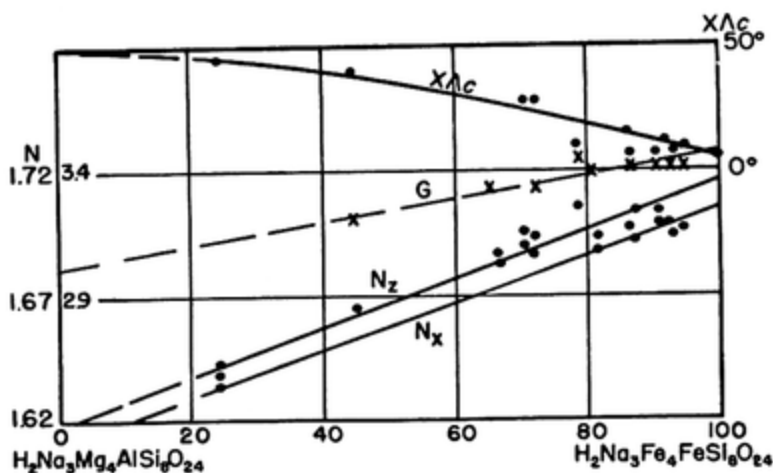


FIG. 335. Properties of the arfvedsonite series.

riebeckites; the optic angle varies from very small in glaucophane to very large in riebeckite. Relations between composition and properties are shown in Figs. 334 and 335, which are only approximations, since soda-hornblende crystals (nearly)

<sup>117</sup> A. Johnson (*N. Jahrb. Min.*, II, 117, 1901) reports  $X \wedge c$  as  $-14^\circ$  to  $+20^\circ$  in arfvedsonite.

always contain other end-members besides those shown on the diagrams. Properties of some examples of soda-hornblende are given in the following table:

Type	2V	N <sub>x</sub>	N <sub>y</sub>	N <sub>z</sub>	N <sub>z</sub> -N <sub>x</sub>	Extinction Angle	G.
Glaucophane <sup>102</sup>	(-)41°	1.615	1.632	1.634	0.019	6°-8°	3.126
			calc.				
Glaucophane <sup>118</sup>		1.665		1.668		7°	
Crossite <sup>102</sup>	?	1.640	?	1.652	0.012	3°	3.184
Crossite <sup>118</sup>		1.669		1.671		12°	
Riebeckite <sup>119</sup>	(+)68°	1.688	?	1.691	0.003	1° ca.	?
Riebeckite <sup>120</sup>	(-)Large	?	1.693	?	Very weak	0°-4°	3.371
Arfvedsonite <sup>121</sup>	(-)?	1.633	1.639	1.642	0.009	44°	?
Arfvedsonite <sup>122</sup>	(-)?	?	1.696	?	0.005	15°	3.447
Kataphorite <sup>102</sup>	(-)Small	1.655	?	1.662	0.007	34°	3.201
Barkevikite <sup>102</sup>	(-)?	1.687	?	1.701	0.014	18°	3.415
Crocidolite <sup>123</sup>	(-)Large	1.64	1.65	1.66	0.02	3°-15°	?
Gastaldite <sup>124</sup>	(-)43°	1.630	1.646	1.649	0.019	4°-8°	3.31
Torendrikite <sup>125</sup>	Large	?	1.665	?	?	40° ca.	3.21
Eckermannite <sup>126</sup>	(-)75°	1.636	1.644	1.649	0.013	25° ca.	3.16

Soda-amphiboles are usually blue to black, but may be green, brown, gray, or colorless; usually strongly pleochroic, variable; examples follow:

	X	Y	Z
Glaucophane	Colorless	Reddish violet	Azure blue
Glaucophane	Bluish green	Lavender-blue	Bluish brown
Glaucophane	Greenish yellow	Violet	Ultramarine blue
Crossite	Colorless to yellow	Sky to dark blue	Deep violet
Riebeckite	Deep blue	Violet	Pale greenish yellow
Riebeckite	Smoky green	Yellow	Green to black
Riebeckite	Green-blue	Clear yellow	Blue-violet
Arfvedsonite	Berlin blue	Violet	Greenish yellow
Arfvedsonite	Deep green	Brown	Greenish brown
Kataphorite	Yellow-red or gray	Brownish red	Reddish yellow
Barkevikite	Light yellow	Reddish brown	Dark brown
Crocidolite	Light yellow	?	Dark yellow
Torendrikite	Sea blue	Violet	Straw yellow

<sup>118</sup> Z. Harada: *Jour. Geol. Soc. Japan*, XLVII, 219 (1940).

<sup>119</sup> L. Alnberg: *Fort. Min. Krist. Pet.*, XIX, 271 (1935).

<sup>120</sup> A. Vendl: *Zeit. Krist.*, LX, 135 (1924).

<sup>121</sup> E. E. Wahlstrom: *Econ. Geol.*, XXXV, 477 (1940).

<sup>122</sup> S. G. Gordon: *Proc. Phila. Acad. Sci.*, LXXIX, 193 (1927).

<sup>123</sup> E. F. Bliss: *Am. Mus. Nat. Hist.*, XXXII, 517 (1913); E. V. Shannon: *J. Wash. Acad. Sci.*, XII, 242 (1922).

<sup>124</sup> S. Kreutz: *Sitzb. Akad. Wiss. Wien*, CXVII, 887 (1908).

<sup>125</sup> A. Lacroix: *C. R. Acad. Sci. Paris*, CLXXI, 594 (1920). N measured by the author.

<sup>126</sup> O. J. Adamson: *Geol. För. Förh. Stockholm*, LXIV, 329 (1942), and LXVI, 113 (1944). N. Sundius: *Sver. Geol. Und. Årsb.*, XI, No. 4 (1946).



**ALTER.** Glaucophane may be the product of alteration of pyroxene, and it may alter to a green soda-amphibole probably rich in  $Ca_2Mg_4Al(OH)_2Si_7AlO_{22}$ ; it then has an extinction angle ( $Z \wedge c$ ) of  $16^\circ$  to  $22^\circ$ , and the color along  $Z$  is pale greenish blue; it has been called "abnormal glaucophane." Riebeckite may alter to siderite and limonite.

**OCCUR.** Glaucophane is found in schists and similar metamorphic rocks. Riebeckite occurs in sodic igneous rocks and some metamorphic rocks. Arfvedsonite, kataphorite, and barkevikite are found in alkaline igneous rocks such as nepheline syenite.

**DIAG.** Soda-hornblende is characterized by cleavages at  $124^\circ$  and (strong) pleochroism, usually in blue. Glaucophane is (pale) blue with positive elongation; riebeckite is deeply colored and strongly pleochroic with negative elongation. Arfvedsonite has negative elongation, strong pleochroism, and an extinction angle usually larger than that of riebeckite and less than that of kataphorite.

**Sérandite**<sup>127</sup> [(Mn,Ca,Na,K,H)SiO<sub>3</sub>?] is monoclinic with  $\beta = 94^\circ 30'$ . Crystals elongated along  $b$  with distinct 001 and 010 cleavages.  $G. = 3.215$ .  $X \wedge c = -57^\circ$ ;  $Z = b$ .  $(+2V = 35.5^\circ$ ,  $N_X = 1.660$ ,  $N_Y = 1.664$ ,  $N_Z = 1.688$ ,  $N_Z - N_X = 0.035$ . Color rose red. Found in nepheline syenite in French Guinea.

**Chevkinite**<sup>128</sup> [(Tschefkinite)—(Fe,Ca)(Ce,La,Al)<sub>2</sub>(Si,Ti)<sub>3</sub>O<sub>10</sub>?] is monoclinic with  $a:b:c = 2.426:1:1.955$ ,  $\beta = 100^\circ 8'$ . No cleavage.  $H. = 5.5$ .  $G. = 4.3-4.65$ .  $F. = 4$ . Gelatinizes with HCl.  $X \wedge c = 11^\circ$  to  $26^\circ$  in obtuse angle  $\beta$ ;  $Z = b$ .  $(-2V =$  medium,  $N_Y = 1.88$ ,  $N_Z - N_X = 0.01$  (Larsen<sup>129</sup>). Again:  $(-2V =$  small,  $N_Y = 1.97$ ,  $N_Z - N_X = 0.02$  (Larsen<sup>129</sup>). Again:  $(+2V = 80^\circ$  to  $(-2V = 78^\circ$ ,  $N = 1.63$  to  $1.68$ ,  $N_Z - N_X = 0.0035$  (altered?) (Boldireff<sup>128</sup>). Also,<sup>130</sup> with 9.56 Fe<sub>2</sub>O<sub>3</sub> and only 12.04 SiO<sub>2</sub>,  $G. = 4.67$ ,  $(-2V =$  moderate with  $r > v$ ,  $N_Y = 1.99$ ,  $N_Z - N_X =$  moderate. Color velvet black with  $X =$  nearly colorless,  $Y =$  pale red-brown,  $Z =$  dark red-brown. Also in part isotropic with  $N = 1.88$ , and in another case  $N = 1.965$ . Found in Madagascar and in the Ilmen Mountains, U.S.S.R.

**Ussingite** (HNa<sub>2</sub>AlSi<sub>3</sub>O<sub>9</sub>) is triclinic and pseudomonoclinic. Perfect 110 and  $\bar{1}\bar{1}0$  cleavages with  $001 \wedge 110 = 70^\circ 21'$ ,  $001 \wedge \bar{1}\bar{1}0 = 71^\circ 30'$ ,  $110 \wedge \bar{1}\bar{1}0 = 90^\circ 28'$ . Common twinning on 010.  $H. = 6.5$ .  $G. = 2.46$ .  $F. =$  easy with swelling. Gelatinizes in HCl. The extinction in the zone normal to 010 is  $0^\circ-6^\circ$ ;  $Z' \wedge c = -33^\circ$  in 010. In sections normal to 001 and 010 the extinction angle to 010 is  $4^\circ$ .  $(+2V$ <sup>131</sup>  $= 36^\circ$ ,  $N_X = 1.504$ ,  $N_Y = 1.509$ ,  $N_Z = 1.545$ ,  $N_Z - N_X = 0.041$ . In 001 flakes the birefringence is 0.016. Color pale to dark violet-red without pleochroism. Found in pegmatite at Kangerdluarsuk, Greenland. The negative relief, strong birefringence, and color are distinctive.

<sup>127</sup> A. Lacroix: *C. R. Acad. Sci. Paris*, CXCII, 189 (1931); *Min. Abst.*, IV, 497 (1931).

<sup>128</sup> A. Boldireff: *Bull. Soc. Fr. Min.*, XLVIII, 120 (1925).

<sup>129</sup> E. S. Larsen: *U. S. Geol. Surv. Bull.* 679 (1921). I. P. Alimarin: *Min. Abst.*, VI, 376 (1937).

<sup>130</sup> A. J. Kauffman and H. W. Jaffe: *Am. Mineral.*, XXXI, 582 (1946).

<sup>131</sup> V. I. Gerasimovsky: *Min. Abst.*, VIII, 222 (1942).

## HYDROUS

SEPIOLITE<sup>132</sup>

## MONOCLINIC



$$a:b:c = 1.478:1:0.339 \quad \beta = 90^\circ-93^\circ$$

COMP. A little Al, Fe, Na, H may be present.  $\text{H}_2\text{O}$  is variable. Formula perhaps  $2\text{MgO} \cdot 3\text{SiO}_2 \cdot 4\text{H}_2\text{O}$ .

STRUC.  $a$  23.2,  $b$  15.7,  $c$  5.32 Å.

PHYS. CHAR. Always finely fibrous; commonly mixed with apparently amorphous material of the same or similar composition, the mixture constituting the substance called *meerschaum*.  $H. = 2-2.5$ .  $G. = 2$ . Dry porous masses float on water.  $F. = 6$ , usually after blackening, giving a burnt odor, and turning white. Sepiolite does not, and para-sepiolite does, gelatinize with HCl.

OPT. PROP. The axis  $Z$  (nearly)  $= c$  (elongation). The optic angle is usually near  $0^\circ$ . See Fig. 336.  $(- )2V = 0^\circ-60^\circ$ ,  $N_X = 1.515-1.520$ ,  $N_Y = ?$ ,  $N_Z = 1.525-1.529$ ,  $N_Z - N_X = 0.009 \pm$ . Again:<sup>133</sup>  $N_X = 1.506$ ,  $N_Z = 1.526$ ,  $N_Z - N_X = 0.020$ . Heated above  $100^\circ$   $N_Z$  becomes 1.535 ca.

*Parasepiolite* has<sup>134</sup>  $(- )2V = 50^\circ$ ,  $N_X = 1.498$ ,  $N_Z = 1.506$ ,  $N_Z - N_X = 0.008$ ; again  $N_X = 1.490$ ,  $N_Z = 1.505$ ,  $N_Z - N_X = 0.015$ . The apparently amorphous part of *meerschaum*, sometimes called  $\beta$ -sepiolite, has  $N = 1.517$  ca.

Color white, pink, greenish, pale yellow. More transparent after immersion in liquid. Colorless in thin section but may be pleochroic in thick sections with  $X =$  colorless to pale yellow,  $Y = Z =$  golden yellow.

INCL. Inclusions may be abundant, of calcite, dolomite, silica, etc.

OCCUR. Sepiolite is found in serpentine as an alteration product.

DIAG. *Meerschaum* is compact with a smooth feel. Sepiolite is much like kaolinite, but has lower refringence.

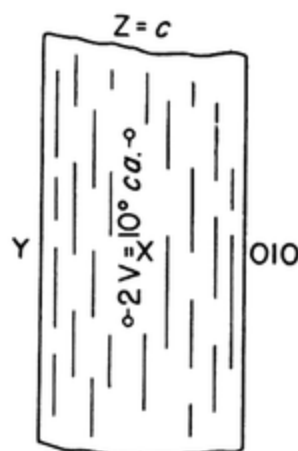


FIG. 336. The optic orientation of sepiolite.

### 3. Type formula $A_mB_3X_7$ Triple chains

*Epididymite*<sup>135</sup> ( $\text{NaBeOHSi}_3\text{O}_7$ ) is orthorhombic dipyramidal with  $a:b:c = 0.579:1:1.075$ . Space group<sup>136</sup>  $Pnma$ ;  $a$  7.32,  $b$  12.63,  $c$  13.58 Å. U.C. 8. Crystals  $\{001\}$  plates, either equant or elongated along  $b$ . Twinning on 001. Perfect 001 and 100 cleavages.  $H. = 5.5$ .  $G. = 2.55$ .  $F. = 3$ . Nearly insoluble in acid. The optic plane is 001;  $Z = a$   $(+ )2V = 22.5^\circ$ ,  $r > v$ .  $N_X = 1.544$ ,  $N_Y = 1.544$ ,  $N_Z = 1.546$ ,  $N_Z - N_X$

<sup>132</sup> H. Longchambon: *C. R. Acad. Sci. Paris*, CC, 949 (1935). Also, G. Migeon: *Bull. Soc. Fr. Min.*, LIX, 6 (1936). S. Caillère: *C. R. Acad. Sci. Paris*, CXCVI, 416 (1933) and CXCIX, 1626 (1934).

<sup>133</sup> J. Daly: *Am. Mineral.*, XX, 651 (1935).

<sup>134</sup> A. J. Kauffman: *Am. Mineral.*, XXVIII, 512 (1943).

<sup>135</sup> *Eudidymite* and *epididymite* are classed as triple-chain structures although the triple chains are connected with each other, though offset.

<sup>136</sup> T. Ito: *Zeit. Krist.*, LXXXVIII, 142 (1934); *Am. Mineral.*, XXXII, 442 (1947).

= 0.002. Colorless. Found in pegmatite, as in Norway and at Narsarsuk, Greenland.

*Eudidymite* <sup>135, 137</sup> ( $NaBeOHSi_3O_7$ ) is monoclinic prismatic with <sup>136</sup>  $a:b:c = 1.712:1:1.898$ ,  $\beta = 103^\circ 43'$ . Space group <sup>138</sup>  $C2/c$ ;  $a$  12.62,  $b$  7.37,  $c$  13.99 Å. U.C. 8. Crystals {001} plates with constant lamellar twinning on 001. Perfect 001 and poor  $\bar{5}51$  cleavages.  $H. = 6$ .  $G. = 2.55$ .  $F. = 3$ . Nearly insoluble. The optic plane is 010;  $Z \wedge c = -58.5^\circ$ .  $(+ )2V = 30^\circ$ ,  $r > v$  distinct.  $N_X = 1.545$ ,  $N_Y = 1.546$ ,  $N_Z = 1.551$ ,  $N_Z - N_X = 0.006$ . Colorless. Found in cavities in zircon syenite, as in Norway and Greenland.

#### 4. Type formula $A_mB_4X_9$ Quadruple chains

##### EPIDOTE GROUP <sup>139</sup>

The epidote group includes several silicates of aluminum and calcium with more or less iron, manganese, cerium, etc. The chief compound,  $Ca_2Al_2OHSi_3AlO_{12}$ , is dimorphous—both orthorhombic and monoclinic—but only monoclinic phases are known for the rest of the group, which may be summarized as follows:

Species	Subspecies	$a:b:c$
Zoisite <sup>140</sup>		0.622:1:0.347 $Ca_2Al_2OHSi_3AlO_{12}$
Epidote	Clinozoisite	1.583:1:1.814 $Ca_2Al_2OHSi_3AlO_{12}$
	Pistacite <sup>141</sup>	1.591:1:1.812 $Ca_2(Al,Fe)_2OHSi_3AlO_{12}$
	Piedmontite	1.559:1:1.778 $Ca_2(Al,Fe,Mn)_2OHSi_3AlO_{12}$
Allanite	Orthite	1.551:1:1.768 $(Ca,Ce,La)_2(Al,Fe''',Fe'')_2OHSi_3AlO_{12}$
	Magnesium orthite	$CaCeMg_2OHSi_3AlO_{12}$
	Nagatelite	$(Ca,Ce)_2(Al,Fe''',Fe'')_2OH(Si,P)_3AlO_{12}$

No continuous series is known as yet between epidote and allanite.

The relation in form between zoisite and epidote is clear when  $a b c$  of zoisite is changed to  $b c a$ ; then for zoisite  $a:b:c = 1.439:1:1.790$ .

The formulas will be expressed in shorter form in the following descriptions.

<sup>137</sup> C. Palache: *Zeit. Krist.*, LXXXVI, 280 (1933).

<sup>138</sup> B. Gossner and O. Kraus: *Cent. Min.*, 1929A, 257.

<sup>139</sup> T. Ito (*Am. Mineral.*, XXXII, 309, 1947) described the quadruple chains of epidote, but further study is needed as to details of the structure. See also F. Machatschki: *Min. Pet. Mit.*, (3), I, 19 (1948).

<sup>140</sup> B. Gossner and F. Mussgnug: *Cent. Min.*, 1930A, 369.

<sup>141</sup> H. Strunz: *Zeit. Krist.*, XCII, 402 (1935).

## ZOISITE

ORTHORHOMBIC DIPYRAMIDAL  $\text{Ca}_2\text{Al}_3(\text{OH})\text{Si}_3\text{O}_{12}$   
 $a:b:c = 0.622:1:0.347$

COMP. A little  $\text{Fe}_2\text{O}_3$  is rather common in zoisite, but when it passes 5 per cent the monoclinic phase is probable. Mn may be present.

STRUC. Space group <sup>140</sup>  $Pnma$ , changing to position like epidote;  $a$  16.21,  $b$  5.63,  $c$  10.08 Å. U.C. 4. (Setting  $Pbnm$  used below.)

PHYS. CHAR. Crystals prismatic, deeply striated vertically. Perfect 010 cleavage.  $H. = 6$ .  $G. = 3.25-3.36$ .  $F. = 3$  with swelling. Insoluble.

OPT. PROP. Iron-free zoisite <sup>142</sup> (called  $\alpha$ -zoisite by Termier <sup>143</sup>) has the optic plane parallel to 010 (= the cleavage) and  $Z$  normal to 100, whereas zoisite with about 5%  $\text{Fe}_2\text{O}_3$  (equals about 10 mol. %  $\text{Ca}_2\text{Fe}_3\text{OHSi}_3\text{O}_{12}$ ) has the optic plane parallel to 001 (normal to the cleavage) and  $Z$  normal to 100. Iron-free zoisite has  $(+ )2V = 30^\circ \pm$ ,  $r < v$  strong. Zoisite with about 5%  $\text{Fe}_2\text{O}_3$  (called  $\beta$ -zoisite by Termier <sup>144</sup>) has  $(+ )2V = 60^\circ$ ,  $r > v$ , distinct. The optic angle passes through  $0^\circ$  between these two; when  $2V = 0^\circ$  for red, sections parallel to 100 and normal to  $Z$  give abnormal blue interference colors; when  $2V = 0^\circ$  for blue, similar sections give a yellowish gray interference color. See Figs. 337 and 338. Zoisite may show variations in these properties in a single crystal, probably due to varying tenor of  $\text{Fe}_2\text{O}_3$  in zones of growth. The birefringence and doubtless the refringence increase with the tenor of  $\text{Fe}_2\text{O}_3$ , but precise data are lacking. See Fig. 339. Data follow:

$\text{Fe}_2\text{O}_3$	$2V$	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$	Authority
?		1.696	1.696	1.702	0.006	
1.47	$37^\circ \pm$	1.7011	1.7020	1.7073	0.0062	Grip <sup>145</sup>
0.92( $\text{FeO} = 4.06$ )		1.705	?	1.710		Yosimura <sup>146</sup>
2.14		1.700	1.703	1.718	0.018	Shannon <sup>147</sup>
0.90( $\text{MnO} = 0.47$ )	$48^\circ$	1.693		1.697	0.004	Shabynin <sup>148</sup>
(Thulite)		1.685-1.705	1.688-1.710	1.698-1.725	0.007-0.022	Glass <sup>149</sup>

<sup>142</sup> F. Becke in Doelter: *Hdb. Mineralch.*, II, 1, 23 (1914).

<sup>143</sup> P. Termier: *Bull. Soc. Fr. Min.*, XXI, 148 (1898), and XXIII, 50 (1900).

<sup>144</sup> A. Orlov (*N. Jahrb. Min.*, I, 39, 1928) argues that Termier's  $\beta$ -zoisite is monoclinic and an iron-poor part of the epidote series.

<sup>145</sup> E. Grip: *Bull. Geol. Inst. Upsala*, XXII, 289 (1930).

<sup>146</sup> T. Yosimura: *Min. Abst.*, VII, 358 (1939).

<sup>147</sup> E. V. Shannon: *U. S. Nat. Mus. Bull.*, CXXXI, 323 (1926).

<sup>148</sup> L. I. Shabynin: *Min. Abst.*, VI, 437 (1937).

<sup>149</sup> W. T. Schaller and J. J. Glass: *Am. Mineral.*, XXVII, 519 (1942).

Color gray, greenish, brown, green; colorless in thin section. *Thulite* is a pink variety whose color seems to be due to manganese, though the tenor is often less than 0.5 per cent; it is pleochroic with X = dark pink, Y = bright pink, Z = yellow.

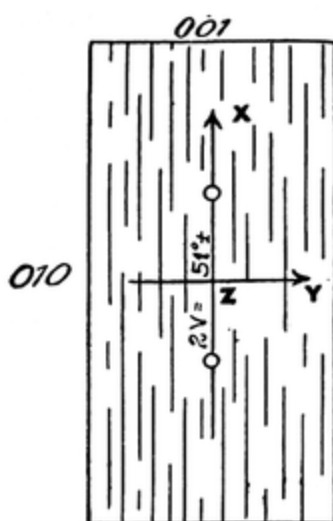


FIG. 337. The optic orientation of iron-free or  $\alpha$ -zoisite.

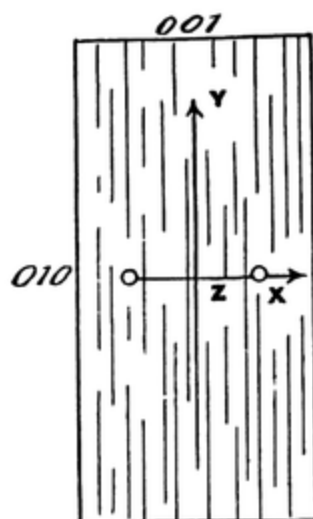


FIG. 338. The optic orientation of ferrian or  $\beta$ -zoisite.

**OCCUR.** Zoisite is found in schists often associated with amphibole; also in igneous rocks as an alteration product of plagioclase; also in quartz veins in altered basic igneous rocks. Zoisite is not so common as clinozoisite; the iron-poor type is more abundant than the ferriferous mineral. *Saussurite* is a feldspar mass more or less completely altered to a mixture of zoisite, new feldspars, actinolite, chlorite, etc.

**DIAG.** Zoisite is distinguished in thin section by elongated sections with parallel extinction, high relief, very weak birefringence, and (often) very strong dispersion. The elongation is negative, or, rarely, plus or minus. Zoisite differs from pistacite in the absence of color and much weaker birefringence, and from clinozoisite in its parallel extinction and smaller optic angle.

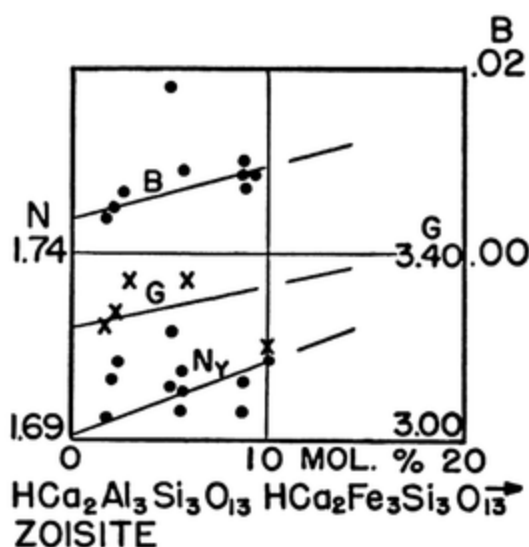
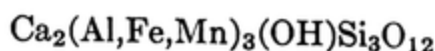


FIG. 339. Properties of zoisite.

## EPIDOTE

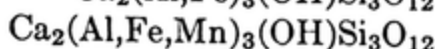
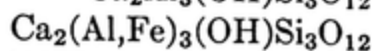
## MONOCLINIC PRISMATIC

 $a:b:c$  $\beta$ 

**Clinozoisite** 1.583:1:1.814 115° 30'

**Pistacite** 1.591:1:1.812 115° 24'

**Piedmontite** 1.559:1:1.778 115° 21'



**COMP.** There is a continuous series from  $\text{Ca}_2\text{Al}_3(\text{OH})\text{Si}_3\text{O}_{12}$  to about 40 mol. %  $\text{Ca}_2\text{Fe}_3(\text{OH})\text{Si}_3\text{O}_{12}$ ; it is called clinozoisite from 0 to 10%, and pistacite from 10–40%. There seems to be a similar series from  $\text{Ca}_2\text{Al}_3(\text{OH})\text{Si}_3\text{O}_{12}$  to about 40%  $\text{Ca}_2\text{Mn}_3(\text{OH})\text{Si}_3\text{O}_{12}$ , but examples are not common. A little Mg, Sr, Ti, Na, etc., may be present; also, as much as 3.8% BeO.

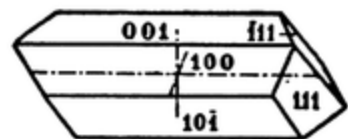


FIG. 340. A crystal habit of epidote.

**STRUC.** Space group  $P2_1/m$ ;  $a$  8.96,  $b$  5.63,  $c$  10.20 Å. U.C. 2. In a different orientation (with  $10\bar{1}$  as the cleavage plane)  $a$  16.39,  $b$  5.63,  $c$  10.20 Å,  $\beta = 98^\circ 57'$ . U.C. 4.

**PHYS. CHAR.** Crystals elongated along  $b$  with striations in the same direction; see Fig. 340; also granular. Perfect 001 cleavage. Twinning

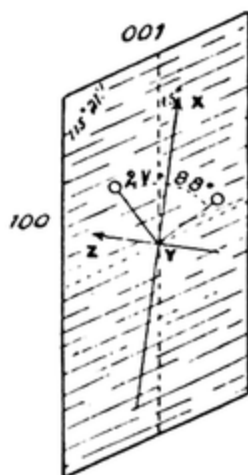


FIG. 341. The optic orientation of pistacite.

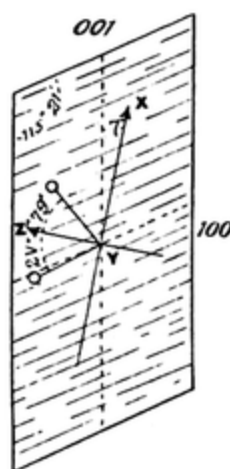


FIG. 342. The optic orientation of piedmontite.

on 100 often lamellar.  $H. = 6-7$ .  $G. = 3.35-3.5$ .  $F. = 3$  with intumesence. Nearly or quite insoluble.

**OPT. PROP.** The optic plane is parallel with 010;  $X \wedge c = 0^\circ$  to  $+12^\circ$ , therefore  $Z \wedge 001$  cleavage =  $25^\circ$  to  $14^\circ$ . See Figs. 341 and 342. The indices, birefringence, and optic angle vary rapidly with the composition—see Fig. 343; such variations are often found in a single crystal (therefore an accurate correlation is difficult). Inclined dispersion strong





Colorless or pale yellow, green, or pink (clinozoisite) to green, yellow, or gray (pistacite) and pleochroic in thin section with  $X < Z < Y$  and  $X$  = colorless, lemon yellow, pale green,  $Y$  = pale blue, greenish yellow,  $Z$  = colorless, yellowish green, pink; or reddish brown to black (piedmontite) and pleochroic with  $X > Y > Z$  and  $X$  = lemon to orange yellow,  $Y$  = amethyst, violet, or pink,  $Z$  = bright red.

By looking through a basal plate of pistacite at a clear sky, absorption figures may be seen, somewhat resembling interference figures. They are called *houppes* or *epoptic figures*, and are produced only by minerals of strong absorption when observed along an optic axis; they are areas of color shaped about like the concave areas of the isogyres of an acute bisectrix interference figure of small optic angle at the  $45^\circ$  position. In epidote they are brown spots on a green field. Such figures are shown also by andalusite, cordierite, tourmaline, and a few other minerals.

**ALTER.** Alteration due to weathering is rare. When epidote is fused and recrystallized, anorthite and augite or meionite, often with magnetite, are produced.

**OCCUR.** Epidote is common in contact zones and schists, and is an alteration product (probably under hydrothermal conditions) of ferromagnesian minerals and feldspars.

**DIAG.** The high refringence, parallel extinction in longitudinal sections with inclined extinction in transverse sections, and (usual) strong birefringence, variable even in a single crystal, are quite characteristic. The forms, color, and pleochroism are also distinctive. Unlike augite, sections showing one cleavage and small or  $0^\circ$  extinction angles have the optic plane normal to the cleavage. Clinozoisite is colorless or nearly so. Piedmontite differs from pistacite in color, pleochroism, and positive optic angle.

*Tawmawite*<sup>156</sup> is a variety of epidote with appreciable Cr replacing Al. With  $\text{Al}:\text{Cr}:\text{Fe}''' = 77:15:8$ , the optic plane is normal to 010;  $X \wedge c = +24^\circ$ ,  $(- )2V = 50^\circ \pm$ ,  $r < v$  distinct,  $N_X = 1.695$  (to 1.70);  $N_Y = ?$ ,  $N_Z = (1.70 \text{ ca. to}) 1.715$ ,  $N_Z - N_X = 0.008$  or less. Abnormal interference colors sometimes. Pleochroic with  $X = Z$  = emerald green,  $Y$  = bright yellow, or  $X$  = olive green,  $Y$  = brown,  $Z$  = emerald green. Alters rather easily. Found at Tawmaw, Burma.

*Hancockite*  $[\text{Ca}(\text{Pb},\text{Sr})(\text{Al},\text{Fe}''')_3(\text{OH})\text{Si}_3\text{O}_{12}]$  is a variety of epidote containing notable quantities of Pb and Sr.  $H. = 6-7$ .  $G. = 4$ .  $F. = 3$ , with intumescence. The optic plane is 010;  $X \wedge c = ?$ ;  $(- )2V = 50^\circ \text{ ca.}$ ,  $r > v$ ;  $N_X = 1.788$ ,  $N_Y = 1.81$ ,  $N_Z = 1.830$ ,  $N_Z - N_X = 0.042$ . Color brownish red; in thick plates,  $X$  or  $Z$  = rose or greenish yellow,  $Y$  = yellowish brown. Found at Franklin, New Jersey, with garnet and axinite.

<sup>156</sup> P. Eskola: *C. R. Soc. Géol. Finlande*, VII, 26 (1933). But Lacroix (*Bull. Soc. Fr. Min.*, LIII, 216, 1930) considered tawmawite to be a chromian jadeite.

**ALLANITE** MONOCLINIC PRISMATIC  $(Ca,Ce,La)_2(Al,Fe''',Fe'',Mg)_3(OH)Si_3O_{12}$   
 $a:b:c = 1.551:1:1.768$   $\beta = 115^\circ 1'$

**Orthite**

$(Ca,Ce,La)_2(Al,Fe''',Fe'')_3(OH)Si_3O_{12}$

**Magnesium orthite**

$CaCeMg_2Al(OH,F)Si_3(O,OH)_{12}$

**Nagatelite**

$(Ca,Ce)_2(Al,Fe''',Fe'')_3(OH)(Si,P)_3O_{12}$

**COMP.** It is assumed that continuous series exist between the varieties given above, but allanite is rare and proof is lacking.

**PHYS. CHAR.** Crystals {100} tablets or acicular parallel to  $b$ ; massive. No dis-

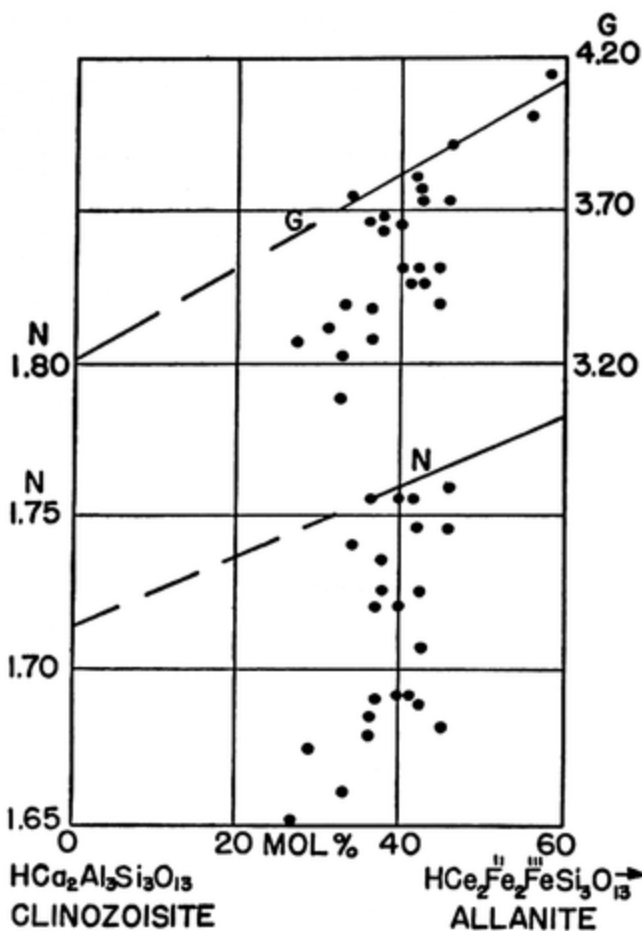


FIG. 344. Properties of allanite.

tinct cleavages.  $H. = 6$ .  $G. = 3.9-4.0$  (as low as 2.7 when altered).  $F. = 2.5$ , with swelling. Gelatinizes with  $HCl$ .

**OPT. PROP.** The optic properties vary decidedly in different cases, doubtless with variations in composition, but precise data are lacking. Frequently the optic plane is 010 and  $X \wedge c = +30^\circ$  to  $+40^\circ$  (also given as "very small" by Lacroix). Often the optic plane is normal to 010 and  $X \wedge c = +22^\circ$  to  $+41^\circ$ .  $(- )2V =$  large,  $r > v$ ; (also  $+$ ?)  $N_X = 1.64$  ca. to  $1.78$  ca.,  $N_Y = 1.65$  ca. to  $1.80$  ca.,  $N_Z = 1.66$  ca. to  $1.81$  ca.,  $N_Z - N_X =$  weak to  $0.036$  (commonly  $0.01$  to  $0.02$ ). The diagram (Fig. 344) shows the pronounced effects of alteration in decreasing both the index

and the specific gravity of allanite. Pleochroic in section with  $X$  = colorless to light brown,  $Y$  = pale green or brown,  $Z$  = green or dark brown.<sup>157</sup>

*Mangan-orthite*<sup>158</sup> is a variety; with 5.37 MnO it has an extinction angle of  $19^\circ$ ;  $(- )2V = 70^\circ$ ,  $N_X = 1.770$ ,  $N_Y = 1.787$  calc.,  $N_Z = 1.795$ ,  $N_Z - N_X = 0.025$ .

*Magnesium orthite*<sup>159</sup>  $[\text{CaCeMg}_2\text{Al}(\text{OH},\text{F})\text{Si}_3(\text{O},\text{OH})_{12}]$  has  $G. = 3.90$ ;  $(+)2V = 50^\circ$ .  $N_X = 1.715$ ,  $N_Y = 1.718$ ,  $N_Z = 1.733$ ,  $N_Z - N_X = 0.018$ ; weakly pleochroic pinkish to brown. There is probably a series from orthite to this variety.

*Nagatelite*<sup>160</sup>  $[(\text{Ca},\text{Ce})_2(\text{Al},\text{Fe}''',\text{Fe}'')_3(\text{OH})(\text{Si},\text{P})_3\text{O}_{12}]$  is probably closely related to allanite.  $H. = 5.5$ .  $G. = 3.91$ . The optic plane is  $010$ ;  $X \wedge c = 32^\circ$ .  $(- )2V = ?$ ,  $N_X = 1.750$ ,  $N_Y = 1.760$ ,  $N_Z = 1.765$ ,  $N_Z - N_X = 0.015$ . Color black with brown streak. Pleochroic with  $X$  = brownish yellow,  $Y$  = reddish brown,  $Z$  = pale yellow, and  $Y > X > Z$ . Found in pegmatite at Nagatejima, Japan.

**ALTER.** Allanite loses its crystal structure (probably owing to radiation from the rare earths) and frequently becomes "metamict" and isotropic; at the same time it acquires water and loses in specific gravity and refringence. For example,  $G.$  may be as low as 3.2 and  $N$  as low as 1.64. According to Larsen the process may be reversed and the mineral may then have  $(- )2V =$  rather large,  $r > v$  distinct,  $X \wedge c = +17^\circ$  to  $+25^\circ$ ,  $N_Y = 1.71$  to  $1.76$ ,  $N_Z - N_X = 0.01$  to  $0.02$ ; pleochroic in red-brown with  $Y$  and  $Z > X$ , the primary mineral being either isotropic or pleochroic in green and yellow.

Allanite is usually heterogeneous but composed in large part of the metamict mineral. It is brown to black in mass and isotropic or pleochroic with  $X$  = yellow to brown,  $Y$  = dark brown,  $Z$  = dark reddish brown. Allanite may produce intense pleochroic halos in biotite.

Allanite may be surrounded by epidote of similar crystal orientation but different extinction position.

**OCCUR.** Allanite is an uncommon accessory constituent of igneous rocks, especially of pegmatites, as at Criffel, Scotland, and Striegau, Silesia. It is also found in gneiss, schists, and magnetite iron ores.

**DIAG.** The high refringence, varying color and properties (even in a single crystal), pleochroism in brown and green, great variations in birefringence, and common association with epidote are distinguishing features.

**Sursassite**<sup>161</sup>  $[\text{MgMn}_4\text{Al}_4(\text{OH})_2\text{Si}_5\text{O}_{20} \cdot 2\text{H}_2\text{O}]$  is monoclinic in acicular crystals elongated along  $b$ . Cleavage parallel to  $b$ , presumably  $001$ . Related to manganepidote.  $G. = 3.25$ . The optic plane is  $010$ ;  $X \wedge c$  (cleavage) =  $55^\circ$ .  $(- )2V =$  moderate,  $r > v$  distinct.  $N_X = 1.736$ ,  $N_Y = 1.755$ ,  $N_Z = 1.766$ ,  $N_Z - N_X = 0.030$ . Color brown with  $X$  and  $Z$  almost colorless and  $Y$  dark reddish brown. Found in veins in Val d'Err, Graubünden.

<sup>157</sup> S. R. B. Cooke and E. S. Perry: *Am. Mineral.*, XXX, 623 (1945).

<sup>158</sup> L. N. Ovchinnikov and M. N. Tzimbalko: *Min. Abst.*, X, 453 (1949).

<sup>159</sup> P. Geijer: *Sver. Geol. Unders. Årsb.*, XX, No. 4 (1927).

<sup>160</sup> S. Iimori et al.: *Am. Mineral.*, XVI, 343 (1931).

<sup>161</sup> J. Jakob: *Schw. Min. Pet. Mit.*, VI, 376 (1926); XIII, 32 (1933). T. Barth and H. Berman: *Chem. Erde*, V, 22 (1930). Sursassite is apparently hydrous, but is included here because of its relation to epidote.

## D. CYCLOSILICATES (RINGS)

1. Trigonal rings with type formula  $A_m(B_3X_9)_n$ 

**Benitoite** ( $BaTiSi_3O_9$ ) is hexagonal (ditrigonal dipyramidal) with  $c/a = 1.471$ . Space group  $^1 C\bar{6}c$ ;  $a$  6.60,  $c$  9.71 Å. U.C. 2. Crystals pyramidal or tabular with poor  $10\bar{1}1$  cleavage.  $H. = 6-6.5$ .  $G. = 3.65$ .  $F. = 3$  to transparent glass. Soluble in HF. Uniaxial positive with  $N_O = 1.757$ ,  $N_E = 1.804$ ,  $N_E - N_O = 0.047$ . Dispersion  $^2 G - B$  for  $N_O = 0.046$ . Color blue, purple, colorless, varying even in a single crystal. Colored parts are pleochroic with  $O =$  colorless,  $E =$  purple, indigo, or greenish blue. Found with natrolite in glaucophane schist in San Benito County, California.

**Wadeite**  $^3 [K_6Ca_3Zr_3(Si_6O_{18})_2]$  is hexagonal in basal plates. It contains some Al, P, Na, Ti, Ba, and H. Poor pyramidal cleavage.  $G. = 3.1$ . Uniaxial positive with  $N_O = 1.625$ ,  $N_E = 1.655$ ,  $N_E - N_O = 0.030$ . Colorless. Found in igneous rock in West Kimberley, Western Australia.

**Diopase**  $^4 (Cu_6Si_6O_{18} \cdot 6H_2O)$  is rhombohedral with  $c/a = 0.534$ . Space group  $^5 R\bar{3}$ ;  $a$  14.66,  $c$  7.83 Å. U.C. 1. Crystals prismatic with perfect  $10\bar{1}1$  cleavage.  $H. = 5$ .  $G. = 3.5$ .  $F. = 7$  but decrepitates with green flame color. Gelatinizes with HCl. Uniaxial positive; also biaxial with three or six sectors in a basal section  $^6$  in which the optic plane is parallel with the edge of the prism and  $2V$  may attain  $45^\circ$ . Data follow:

	Lacroix $^7$	Quercigh $^8$	Galbraith $^9$
$N_O =$	1.644	1.6537-1.6584 D	1.654
$N_E =$	1.697	1.7085-1.7094	1.708
$N_E - N_O =$	0.053	0.0510-0.0513	0.054

$N_E' - N_O$  on the cleavage  $^{10} = 0.014$ .

Diopase is found in copper deposits as at Resbánya, Hungary; Copiapo, Chile; and Clifton, Arizona.

**Eudialyte**  $^{11} [(Na,Ca,Fe)_6ZrSi_6O_{18}(OH,Cl)?]$  is remarkably variable in composition and of uncertain formula. The variety *eucolite* contains much Ce and some Mn. The mineral is hexagonal scalenohedral with  $c/a = 2.11$ . Space group  $R\bar{3}m$ ;  $a$  13.01 Å for the rhombohedral cell. Crystals varied with distinct 0001 cleavage.  $H. = 5-6$ .  $G. = 2.8-3.1$ .  $F. = 2.5$ . Gelatinizes with HCl. Uniaxial positive (eudialite) or negative (eucolite). An intermediate type is sensibly isotropic. Also biaxial,  $2E$  reaching  $50^\circ$ .

$^1$  W. H. Zachariasen: *Zeit. Krist.*, LXXIV, 139 (1930).

$^2$  C. J. Payne: *Min. Abst.*, VII, 518 (1940).

$^3$  R. T. Prider: *Mineral. Mag.*, XXV, 373 (1939).

$^4$  N. V. Belov: *Min. Abst.*, IX, 45 (1944).

$^5$  C. Gottfried: *N. Jahrb. Min.*, A, Bl. Bd. LV, 393 (1926).

$^6$  A. Karnojitsky: *Zeit. Krist.*, XIX, 593 (1891).

$^7$  A. Lacroix: *Minéral. France* (1893).

$^8$  E. Quercigh: *N. Jahrb. Min.*, I, 159 (1916).

$^9$  F. W. Galbraith and T. H. Kuhn: *Am. Mineral.*, XXV, 708 (1940).

$^{10}$  H. Buttgenbach: *Minéraux et Roches*, 508 (1916).

$^{11}$  W. H. Zachariasen: *Cent. Min.*, 1930A, 315.

Eudialyte <sup>12</sup>	Intermediate	Eucolite <sup>13</sup>
$N_O = 1.593$ ca. to $1.610$	$1.607$ ca.	$1.620$ to $1.643$
$N_E = 1.597$ ca. to $1.611$	$1.607$ ca.	$1.618$ to $1.634$ ca.
$N_E - N_O = 0.004$ to $0.001$	$0.000$	$N_O - N_E = 0.001$ to $0.010$ ca.

Zoned crystals may vary in birefringence from 0.000 to 0.009.

Color pale pink, carmine, red, brown. In thin section usually colorless, but very variable even in a single crystal; in thick section  $a$  = yellow to colorless,  $c$  = carmine to bright yellow, and  $a < c$ , independent of the optic sign. Found in nepheline syenite and granite, as at Kangerdluarsuk, Greenland, and Magnet Cove, Arkansas. The pleochroism, weak birefringence, and association with soda minerals are distinctive; lower refringence than birefringent garnet.

*Giannettite*<sup>14</sup> is chemically like eudialyte, but it contains some Ti and Mn and is triclinic. Crystals prismatic with perfect 100 and poor 010 and 001 cleavages. Multiple twinning on 100 common.  $Y \wedge c = 23^\circ$ .  $(+ )2V = 30^\circ$ ,  $N_X = 1.663$ ,  $N_Y = 1.664$ ,  $N_Z = 1.675$ ,  $N_Z - N_X = 0.012$ . Found in tinguaitite of Brazil.

*Pennaite*<sup>14</sup> is chemically like giannettite but is pseudomonoclinic. Crystals prismatic, twinning common.  $Y \wedge c = 13^\circ$ .  $(+ )2V = 25^\circ$ ,  $N_X = 1.696$  calc.,  $N_Y = 1.70$ ,  $N_Z = 1.74$  calc.,  $N_Z - N_X = 0.044$ . Color brown with marked pleochroism:  $X$  = dirty yellow,  $Y$  = grayish yellow,  $Z$  = yellowish brown. Found in lujavrite in Brazil.

*Lovozerite*<sup>15</sup>  $[(H,Na,K,Ca,Mn)_6(Zr,Ti)Si_6O_{16}(OH)_3]$  seems to be eudialyte with less alkali and more H. Granular. Twinning with the principal axes at about  $73^\circ$  may be polysynthetic.  $H. = 5$ .  $G. = 2.38$ . Uniaxial negative with  $N_O = 1.561$ ,  $N_E = 1.549$ ,  $N_O - N_E = 0.012$ . Color black with brown streak; pink in section. Found in volcanic rocks of the Lovozero tundra of the Kola peninsula, U.S.S.R.

*Catapleite*  $(Na_2ZrSi_3O_9 \cdot 2H_2O)$  is dihexagonal dipyramidal with  $c/a = 1.360$ . Space group<sup>16</sup>  $C6/mmc$ ;  $a$  7.39,  $c$  10.05 Å. U.C. 2. It may become monoclinic (also orthorhombic?<sup>17</sup>) below  $140^\circ$ , especially if it has Ca replacing some Na. Then  $a:b:c = 1.733:1:1.362$ ,  $\beta = 89^\circ 49'$ . Crystals thin {001} plates with pseudohexagonal twinning on 110 and perfect 110 and 010 cleavages.  $H. = 6$ .  $G. = 2.75$ .  $F. = 3$ . Soluble in HCl. The optic plane is 010;  $Z$  nearly normal to 001.  $(+ )2E = 30^\circ - 60^\circ$ ,  $r < v$  weak.  $N_X = 1.591$ ,  $N_Y = 1.592$ ,  $N_Z = 1.627$ ,  $N_Z - N_X = 0.036$ . Color yellow to brown; bluish. Found in pegmatite. Very rare. In a type described as orthorhombic<sup>17</sup> the optic plane is 010;  $X = c$ .  $(- )2V =$  large,  $N_X = 1.575$ ,  $N_Y = 1.590$ ,  $N_Z = 1.605$ ,  $N_Z - N_X = 0.030$ . Colorless or buff. Found in pegmatite at Låven, Norway, etc.

*Stokesite*  $(CaZnSi_3O_9 \cdot 2H_2O)$  is orthorhombic with  $a:b:c = 0.346:1:0.804$ . Crystals pyramidal with large {010} faces. Perfect 110 and poor 010 cleavages.  $H. = 6$ .  $G. = 3.19$ . The optic plane is 010;  $X = a$ .  $(+ )2V = 69.5^\circ$ ,  $r < v$ .  $N_X = 1.609$ ,  $N_Y = 1.6125$ ,  $N_Z = 1.619$ ,  $N_Z - N_X = 0.010$ . Colorless. Found with axinite at St. Just, Cornwall.

*Elpidite*<sup>18</sup>  $(H_6NaZrSi_6O_{18})$  is orthorhombic with  $a:b:c = 0.512:1:0.978$ . Crystals fibrous with 110 cleavage.  $H. = 7$ .  $G. = 2.58$ .  $Y = b$ ;  $Z = a$ ; elongation

<sup>12</sup> E. Kostyleva: *N. Jahrb. Min.*, 1931A, 363.

<sup>13</sup> A. Lacroix: *Bull. Soc. Fr. Min.*, XXXVIII, 278 (1915); *Minéral. Madagascar*, I, 588 (1922).

<sup>14</sup> D. Guimarães: *Inst. Tec. Ind. Bol.*, VI, 62 (1948).

<sup>15</sup> V. I. Gerasimovsky: *Min. Abst.*, VII, 468 (1940).

<sup>16</sup> B. K. Brunovsky: *Min. Abst.*, VI, 180 (1936).

<sup>17</sup> S. G. Gordon: *Proc. Phila. Acad. Sci.*, LXXVI, 258 (1924).

<sup>18</sup> G. Flink: *Medd. Grønland*, XXIV, 146 (1901).



negative.  $(+ )2V = 75^\circ$ ,  $r < v$  distinct.  $N_X = 1.560$ ,  $N_Y = 1.565$ ,  $N_Z = 1.574$ ,  $N_Z - N_X = 0.014$ . Color white to brick red. Found in pegmatite in Greenland. Lacroix<sup>19</sup> has described a similar mineral with refringence less than that of albite and  $2V$  variable to  $89^\circ$ . A variety with  $Ti > Zr$  has been called *titanelpidite*.<sup>20</sup> It has  $H. = 6.5$ ,  $G. = 2.55$ ;  $Y = c$ ,  $Z = a$ , and  $(+ )2V = 42^\circ - 43^\circ$ ,  $r < v$  distinct,  $N_X = 1.681$ ,  $N_Y = 1.686$ ,  $N_Z = 1.698$ ,  $N_Z - N_X = 0.017$ . Pleochroic with  $X =$  colorless,  $Z =$  yellow. Found in the Khibinsky region, U. S. S. R.

**Xonotlite** ( $Ca_3Si_3O_9 \cdot H_2O?$ ) is monoclinic<sup>21</sup> with  $a:b:c = 1.165:1:0.958$ ,  $\beta = 90^\circ$  ca.  $a = 8.55$ ,  $b = 7.34$ ,  $c = 7.03$  Å. U.C. 2. Crystals elongated parallel to  $b$  with longitudinal cleavage assumed to be 001.  $H. = 6.5$ .  $G. = 2.71$ .  $F. = 2.5$ . Soluble in HCl. The optic plane is 100 and  $Z = b$ .  $(+ )2V =$  very small,<sup>22</sup>  $N_X = N_Y = 1.583$ ,  $N_Z = 1.593$ ,  $N_Z - N_X = 0.010$ . Colorless to pink; color may fade on exposure to light. Found in limestone near igneous contacts at Tetela de Xonotla, Mexico.

**Leucospheinite**<sup>22a</sup> [ $Na_4Ba(Ti,Zr,Si)_3Si_9O_{27}?$ ] is monoclinic with  $a:b:c = 0.581:1:0.850$ ,  $\beta = 93^\circ 23'$ . Crystals vertically elongated or {001} plates. Often twinned on 001; distinct 010 cleavage.  $H. = 6.5$ .  $G. = 3.05$ .  $F. = 6$ . Decomposed by HF. The optic plane is normal to 010;  $X \wedge a = 0.5^\circ$ ;  $Y \wedge c = -3^\circ$ .  $(+ )^{23} 2V = 77^\circ$ ,  $r > v$ , distinct.  $N_X = 1.645$ ,  $N_Y = 1.661$ ,  $N_Z = 1.688$ ,  $N_Z - N_X = 0.043$ . Color white. Found at Narsarsuk, Greenland.

**Didymolite**<sup>24</sup> ( $Ca_2Al_5Si_8AlO_{27}?$ ) is monoclinic with  $a:b:c = 0.60:1:0.287$ ,  $\beta = 106^\circ$ . Crystals show {010}, {110}, {011}, with twinning on 110, sometimes also on 010. Fair 010 and 110 cleavages.  $H. = 4.5$ .  $G. = 2.71$ .  $F. = 6$ . Insoluble except in HF. The optic plane is 010;  $X \wedge c = 40^\circ$ .  $(- )2V = 78^\circ - 87^\circ 30'$ ,  $r > v$ ,  $N_Y = 1.501$ ,  $N_Z - N_X = 0.015$ . Color dark gray. Colorless in thin section. Found in limestone near nepheline syenite in the Yenesei district, Siberia.

**Alamosite**<sup>25</sup> ( $PbSiO_3$ ) is monoclinic with  $a:b:c = 1.375:1:0.924$ ,  $\beta = 95^\circ 50'$ . Crystals fibrous parallel to  $b$  with perfect 010 cleavage.  $H. = 4.5$ .  $G. = 6.49$ .  $F. = 3$ . Soluble in  $HNO_3$  leaving silica jelly. The optic plane is 010;  $(- )2V = 65^\circ$ ,  $r < v$  strong, with weak inclined dispersion.  $N_X = 1.947$ ,  $N_Y = 1.961$ ,  $N_Z = 1.968$ ,  $N_Z - N_X = 0.023$  (meas.). Colorless or white, with adamantine luster. Found with quartz, cerussite, wulfenite, etc., at Alamos, Mexico.

#### PARAWOLLASTONITE<sup>26</sup> MONOCLINIC PRISMATIC (Ca,Fe,Mn,Mg)SiO<sub>3</sub>

$$\frac{1}{2} a:b:c = 1.052:1:0.965 \quad \beta = 95^\circ 25'$$

COMP.  $CaSiO_3$  can take into crystal solution<sup>27</sup> up to 8%  $MgSiO_3$ , 67%  $FeSiO_3$ , and much  $MnSiO_3$ . See Figs. 346, 347, and 348.

<sup>19</sup> A. Lacroix: *C. R. Acad. Sci. Paris*, CLXXIII, 267 (1921).

<sup>20</sup> A. N. Labuntzov: *Min. Abst.*, III, 235 (1927).

<sup>21</sup> H. Berman: *Am. Mineral.*, XXII, 391 (1937).

<sup>22</sup> E. S. Larsen: *Am. Jour. Sci.*, CXCI, 464 (1917), and *Am. Mineral.*, VIII, 181 (1923); see also E. V. Shannon: *Am. Mineral.*, X, 12 (1925), and *Proc. U. S. Nat. Mus.*, LXVI, Art. 28 (1925).

<sup>22a</sup> G. Flink: *Medd. Grønland*, XXIV, 137 (1901).

<sup>23</sup> E. S. Larsen: *U. S. Geol. Surv. Bull.* 679 (1921).

<sup>24</sup> A. Meister: *Verh. Min. Ges.*, XXXVI, 151 (1908).

<sup>25</sup> C. Palache and H. E. Merwin: *Zeit. Krist.*, XLVI, 513 (1909).

<sup>26</sup> M. A. Peacock: *Am. Jour. Sci.*, XXX, 495 (1935).

<sup>27</sup> J. B. Ferguson and H. E. Merwin: *Am. Jour. Sci.*, CXC VIII, 165 (1919).

STRUC. Space group <sup>28</sup>  $P2_1/c$ ;  $a$  15.33,  $b$  7.28,  $c$  7.07 Å. U.C. 12.

PHYS. CHAR. Crystals commonly {100} or {001} tablets with perfect 100 and good 001 and  $\bar{1}02$  cleavages; poor  $\bar{1}01$  and 101 cleavage or parting. Twinning on 100.  $H. = 4.5-5$ .  $G. = 2.915$ .  $F. = 1540^\circ$  after inversion at  $1200^\circ$  to pseudowollastonite. Decomposed by HCl.

OPT. PROP. The plane of the optic axes is parallel to 010 and normal to the elongation,<sup>29</sup> which is commonly parallel to  $b$ . The acute bisectrix  $X$  makes an angle of  $34^\circ$  with  $c$  in the acute angle  $\beta$ . See Fig. 345. The optic angle is moderate with  $r > v$ , weak, and distinct inclined dispersion. Optic data follow:

	(-) $2V$	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$
California <sup>30</sup>	$35^\circ$	1.614	1.629	1.631	0.017
Hungary <sup>31</sup>	$40^\circ$ ca.	1.621	1.633	1.635	0.014
Finland <sup>32</sup>	.....	1.619	1.632	1.634	0.015

Color white or gray; rarely yellowish; colorless in thin section.

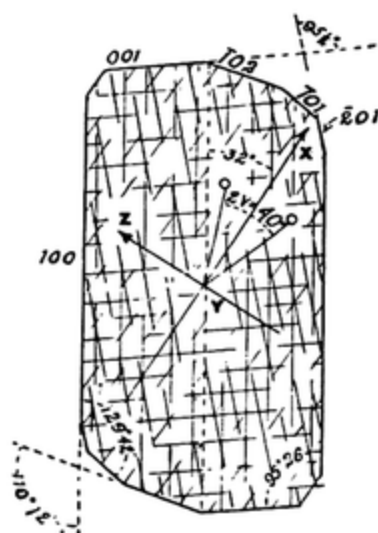


FIG. 345. The optic orientation of parawollastonite.

INVER. An easily reversible inversion occurs at  $1200^\circ$  to pseudowollastonite, which is pseudohexagonal and probably monoclinic. It forms equant grains with basal cleavage and  $H. = 5$ ;  $G. = 2.905$ .  $(+ )2E = 0^\circ$  to  $8^\circ$ ,  $N_X = 1.610$ ,  $N_Y = 1.611$ ,  $N_Z = 1.651$ ,  $N_Z - N_X = 0.041$ . It may show lamellar twinning on 001 with  $X \wedge a = 2^\circ$ . Colorless. Found in slags; also in marls modified by combustion of hydrocarbons in Iran; <sup>33</sup> here it is (nearly) uniaxial with  $N_O = 1.614$ ,  $N_E = 1.648$ ,  $N_E - N_O = 0.034$ .

ALTER. Parawollastonite alters easily to calcite.

OCCUR. It is found especially in contacts of igneous intrusions into limestone, often associated with diopside, garnet, epidote, and calcite.

DIAG. It differs from tremolite and pectolite by its variable sign of elongation and weaker birefringence, and from zoisite and clinozoisite by its lower refringence and smaller optic angle.

## WOLLASTONITE <sup>34</sup>

TRICLINIC PEDIAL

$(Ca, Fe, Mn)SiO_3$

$a:b:c = 1.082:1:0.965$

$\alpha = 90^\circ 0'$

$\beta = 95^\circ 16'$

$\gamma = 103^\circ 22'$

COMP.  $CaSiO_3$  can take into crystal solution up to 67%  $FeSiO_3$ , and much  $MnSiO_3$ .

PHYS. CHAR. Crystals commonly {100} or {001} tablets with perfect 100 and

<sup>28</sup> M. Barnick: *Naturw.*, XXIII, 770 (1935). See also B. Gossner and F. Muschnug: *Cent. Min.*, 1929A, 175.

<sup>29</sup> The writer finds elongation of positive sign in all sections of wollastonite from Bingham, Utah, which is perhaps due to elongation parallel to  $10\bar{2}$ .

<sup>30</sup> A. S. Eakle: *Bull. Dept. Geol. Univ. Calif.*, X, 327 (1917).

<sup>31</sup> Michel-Lévy and Lacroix: *C. R. Acad. Sci. Paris*, CVI, 778 (1888).

<sup>32</sup> E. Mallard: *C. R. Acad. Sci. Paris*, CVII, 302 (1888).

<sup>33</sup> W. F. P. McLintock: *Mineral. Mag.*, XXIII, 207 (1932).

<sup>34</sup> M. A. Peacock: *Am. Jour. Sci.*, XXX, 495 (1935).  $a$  and  $b$  need to be interchanged to make  $b > a$ , but are left unchanged to show the relation to parawollastonite.

good 001 and  $\bar{1}02$  cleavages.  $H. = 4.5-5$ .  $G. = 2.915$ .  $F. = 1540^\circ$ . Decomposed by HCl.

**OPT. PROP.** The optic axial plane makes an angle of  $4^\circ$  with  $b$ , the axis of the cleavage zone.  $X \wedge c = 31^\circ$  in the acute angle  $\beta$ .  $(-)2V = 39^\circ$ ,  $r > v$ .  $N_X = 1.620$ ,  $N_Y = 1.632$ ,  $N_Z = 1.634$ ,  $N_Z - N_X = 0.014$ . A sample<sup>35</sup> containing 8.3 FeO and 1.2 MnO has  $G. = 3.1$  and  $X \wedge c = 44^\circ$  in a section normal to the zone of cleavages; also  $(-)2V = 60^\circ$ .  $N_X = 1.640$ ,  $N_Z = 1.653$ ,  $N_Z - N_X = 0.013$ ;

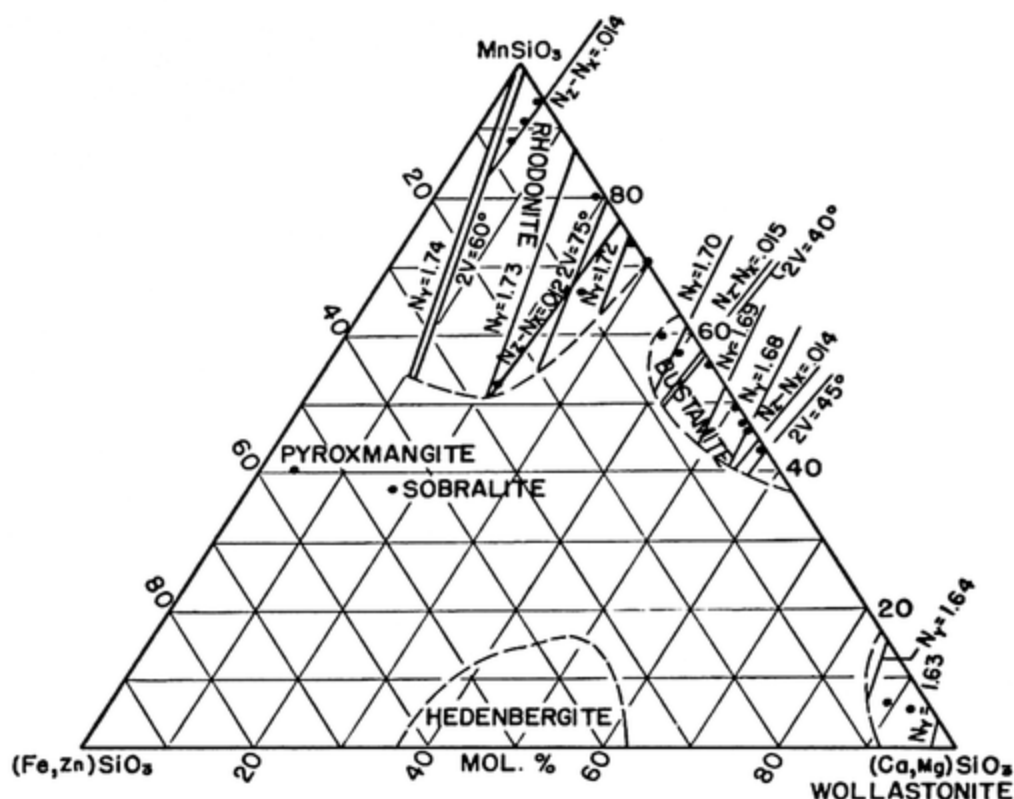


FIG. 346. Relations between composition and optic properties in the  $MnSiO_3$ - $FeSiO_3$ - $CaSiO_3$  discontinuous system. After N. Sundius: *Am. Mineral.*, XVI, 411 and 488 (1931).

$\therefore N_Y = 1.650$ . The relations between optic properties and composition in the  $MnSiO_3$ - $FeSiO_3$ - $CaSiO_3$  discontinuous system are shown in Fig. 346. The properties of artificial wollastonite containing 67%  $FeSiO_3$  are shown in Fig. 347.

**OCCUR.** Wollastonite is found in crystalline limestone at Crestmore, California; it is often closely associated with parawollastonite, as at Monte Somma, Italy.

**DIAG.** Wollastonite and parawollastonite are almost identical in their properties, except for the extinction angle between the optic plane and the axis of the twinning zone, which is  $4^\circ$  in wollastonite and  $0^\circ$  in parawollastonite.

**Bustamite**<sup>36</sup> ( $CaMnSi_2O_6$ ) is triclinic with  $a:b:c = 1.067:1:0.959$ ,  $\alpha = 92^\circ 8'$ ,  $\beta = 94^\circ 54'$ ,  $\gamma = 101^\circ 35'$ . Space group  $P1(?)$ ;  $a$  7.64,  $b$  7.16,  $c$  6.87 Å. U.C. 3. Closely related to triclinic wollastonite, but apparently not forming an isomorphous series with it. See Fig. 348. Very perfect 100, good 110 and  $\bar{1}\bar{1}0$ , and poor 010

<sup>35</sup> C. E. Tilley: *Am. Mineral.*, XXXIII, 736 (1948).

<sup>36</sup> H. Berman and F. A. Gonyer: *Am. Mineral.*, XXII, 215 (1937);  $a$  and  $b$  interchanged to make  $b > a$ .

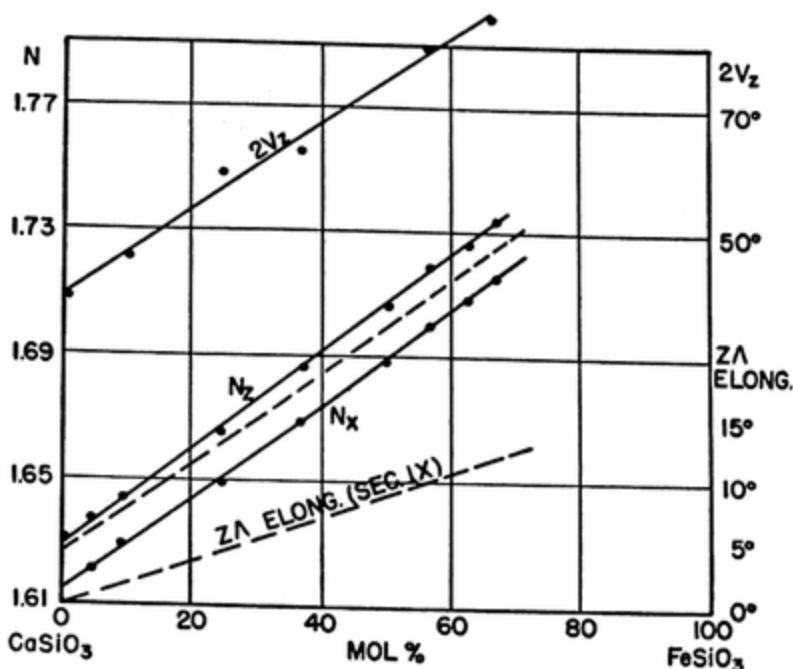


FIG. 347. Properties of the  $\text{CaSiO}_3$ - $\text{FeSiO}_3$  discontinuous series. The properties of hedenbergite differ markedly from those of ferroan wollastonite with  $\text{Ca}:\text{Fe} = 1:1$ .

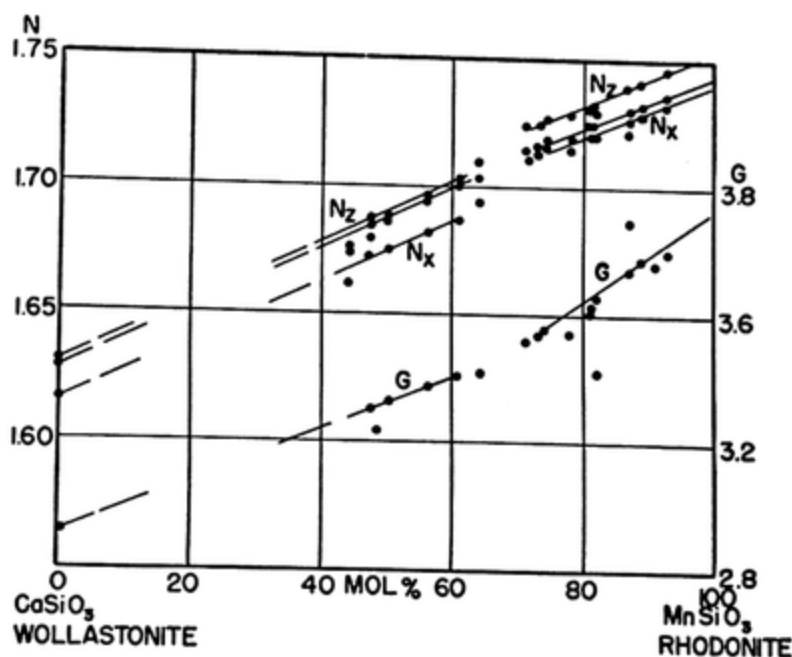


FIG. 348. Properties of the  $\text{CaSiO}_3$ - $\text{MnSiO}_3$  discontinuous series. See N. Sundius: *Am. Mineral.*, XVI, 411 and 488 (1931).

cleavages. Cleavage angle between 010 and 100 is  $94^\circ 33'$  and between 100 and  $\bar{1}\bar{1}0$  is  $44^\circ 58'$ . The optic plane and X are nearly normal to 100 in which  $Z' \wedge c = 36^\circ$ . See Fig. 350.  $(- )2V = 44^\circ$ ,  $r < v$  weak, with strong crossed dispersion.  $N_X = 1.662$ ,  $N_Y = 1.674$ ,  $N_Z = 1.676$ ,  $N_Z - N_X = 0.014$  (Larsen<sup>37</sup>); with  $\text{Ca}:(\text{Fe}, \text{Mg}):\text{Mn} = 34:18:48$ ,  $G = 3.43$ ,  $(- )2V = 35^\circ$ ,  $N_X = 1.692$ ,  $N_Y = 1.705$ ,  $N_Z = 1.707$ ,

<sup>37</sup> E. S. Larsen and E. V. Shannon: *Am. Mineral.*, VII, 95 (1922).

$N_Z - N_X = 0.015$  (Tilley<sup>38</sup>);  $N_X = 1.6720$ ,  $N_Y = 1.6849$ ,  $N_Z = 1.6867$ ,  $N_Z - N_X = 0.0147$  (Sundius<sup>39</sup>). Color pink, fading in light. Found at Franklin, New Jersey.

**RHODONITE**TRICLINIC PINACOIDAL<sup>40</sup> $(Mn, Fe, Ca)SiO_3$ 

$a:b:c = 0.616:1:0.541$      $\alpha = 85^\circ 10'$      $\beta = 94^\circ 4'$      $\gamma = 111^\circ 29'$

COMP. Ideal rhodonite is  $MnSiO_3$ , but natural rhodonite usually contains 5–40 mol. % of  $(Ca, Fe, Zn, Mg)SiO_3$ . See Fig. 334.

STRUC. Space group  $P\bar{1}(?)$ .  $a$  7.77,  $b$  12.45,  $c$  6.74. U.C. 16(?).

PHYS. CHAR. Crystals often rough {001} tablets with perfect 100 and 010 and good 001 cleavages. See Fig. 349.  $H. = 5.5$ – $6.5$ .  $G. = 3.7$ .  $F. =$  about  $1200^\circ$ .

OPT. PROP. In rhodonite with 17%  $CaSiO_3$  and 6%  $FeSiO_3$   $X$  is normal to a plane making angles of  $51^\circ 40'$  with 001 and  $51^\circ 47'$  with 010;  $Z$  is normal to a plane making angles of  $80^\circ 55'$  with 001 and  $50^\circ 7'$  with 010; the extinction on 110 is at  $32^\circ 26'$  to 100 and  $44^\circ 16'$  to 001; the extinction on  $1\bar{1}0$  is at  $10^\circ 48'$  to 110 and  $97^\circ 56'$  to 001; the extinction on 001 is at  $54^\circ 27'$  to 100 and  $39^\circ 37'$  to 010. Variations in the optic orientation of rhodonite and of bustamite and sobralite are shown in Fig. 350 as determined by Sundius<sup>41</sup> (using the old orientation).  $(+ )2V = 61^\circ$ – $75^\circ$ ,  $r < v$  weak, with marked crossed dispersion.  $N_X^{41} = 1.711$ – $1.733$ ,  $N_Y = 1.715$ – $1.737$ ,  $N_Z = 1.724$ – $1.747$ ,  $N_Z - N_X = 0.011$ – $0.014$ . Relations between composition and properties are shown in Figs. 346 and 348, but studies<sup>42</sup> of artificial crystals indicate a continuous series in the high-temperature phase from  $CaSiO_3$  at least to 90%  $MnSiO_3$  with no break in the melting-point curve or the refractive index or density variations. Also artificial crystals<sup>43</sup> may contain from 0 to 50%  $MgSiO_3$ ; with 50%:  $N_Y = 1.678$  and  $(+ )2V = 43^\circ$ .

Color reddish, pink, yellowish, or gray; brown to black by alteration. Colorless in thin section, but in thick plates  $X =$  clear reddish yellow,  $Y =$  pinkish red,  $Z =$  pale reddish yellow; but the chief axes of absorption and pleochroism coincide only roughly with the vibration axes  $X, Y, Z$ .

Fowlerite is probably zinkian rhodonite.  $G. = 3.67$ . A section parallel to 110 shows two cleavages at  $68^\circ$  with extinction at  $22^\circ$  to 001.  $(+ )2V =$  moderate to large,  $r < v$  distinct,  $N_X = 1.687$ – $1.726$ ,  $N_Y = 1.692$ – $1.730$ ,  $N_Z = 1.709$ – $1.737$ ,  $N_Z - N_X = 0.022$ – $0.011$ . Color pink to brownish. Found at Franklin, New Jersey.

ALTER. Rhodonite changes easily by weathering to pyrolusite, or to rhodochrosite and then to pyrolusite.

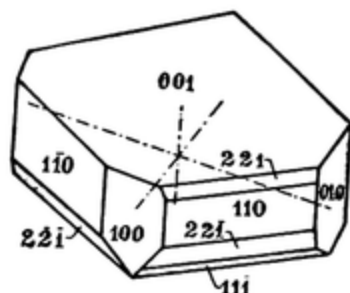


FIG. 349. A crystal habit of rhodonite.

<sup>38</sup> C. E. Tilley: *Mineral. Mag.*, XXVII, 236 (1946).

<sup>39</sup> N. Sundius: *Am. Mineral.*, XVI, 411 and 488 (1931).

<sup>40</sup> M. Perutz: *Mineral. Mag.*, XXIV, 573 (1937). 100, 010, and 001 =  $\bar{1}10$ ,  $1\bar{1}0$ , and 001 of the old orientation.

<sup>41</sup> N. Sundius: *Am. Mineral.*, XVI, 411 and 488 (1931); see also J. Jakob: *Schw. Min. Pet. Mit.*, III, 236 (1925), and E. S. Larsen: *U. S. Geol. Surv. Bull.* 679 (1921). A. Hietanen: *Bull. Com. Géol. Finlande*, 115, 387 (1936), gives  $N_X = 1.739$ ,  $N_Y = 1.748$ ,  $N_Z = 1.760$ ,  $N_Z - N_X = 0.021$ .

<sup>42</sup> E. Voos: *Zt. anorg. Chem.*, CCXXII, 201 (1935).

<sup>43</sup> N. L. Dilakorsky: *Min. Abst.*, X, 464 (1949).

**OCCUR.** It is found in ore deposits of manganese, iron, copper, etc., usually closely associated with rhodochrosite; localities include Långban, Sweden; Xonotla, Mexico; Hinsdale, New Hampshire, etc.

**DIAG.** It differs from monoclinic pyroxenes in having inclined extinction in all sections of the vertical zone; it has weaker birefringence than any pyroxene except enstatite and clinoenstatite; it is rich in manganese.

**Pyroxmangite**  $[(\text{Mn}, \text{Ca})(\text{Fe}, \text{Mg})\text{Si}_2\text{O}_6]$  is triclinic with  $a:b:c = 0.43:1:0.39$ ,  $\alpha = 83^\circ$ ,  $\beta = 94^\circ$ ,  $\gamma = 113^\circ$  (using the orientation with 100, 001, and 010 as the cleavages).  $a$  7.4,  $b$  17.1,  $c$  6.7 Å.  $H. = 5.5-6$ .  $G. = 3.5-3.8$ .  $F. = 3$ . Insoluble

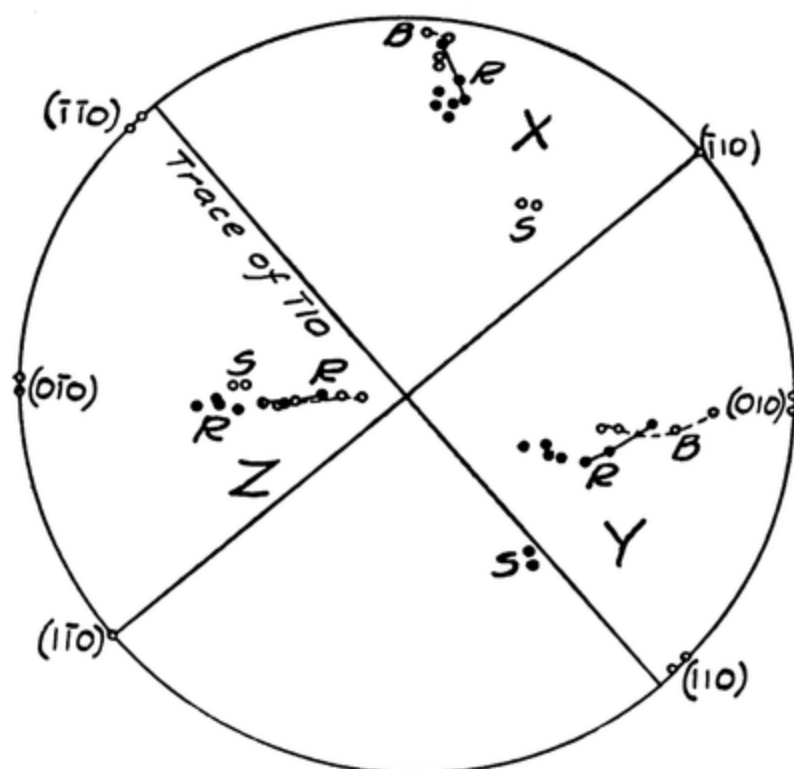


FIG. 350. The optic orientation of rhodonite (*R*), bustamite (*B*), and sobralite (*S*). After N. Sundius: *Am. Mineral.*, XVI, 411 and 488 (1931).

in acids. The optic plane makes an angle of  $35^\circ$  to  $45^\circ$  with the 100 cleavage and about  $85^\circ$  with the 001 cleavage. See Fig. 345.  $(+2V) = 45^\circ$  ca.,  $r > v$ .  $N_X = 1.737-1.748$ ,  $N_Y = 1.740-1.750$ ,  $N_Z = 1.754-1.764$ ,  $N_Z - N_X = 0.017$  ca. Color brown to yellowish. Alters to a black oxide of iron and manganese. *Sobralite* is a synonym.<sup>45</sup> Found<sup>45</sup> at Tunaberg, Sweden; Iva, South Carolina, and Boise, Idaho.

#### PECTOLITE<sup>46</sup>

TRICLINIC PINACOIDAL



$$a:b:c = 1.137:1:0.999$$

$$\alpha = 90^\circ 24'$$

$$\beta = 95^\circ 14'$$

$$\gamma = 102^\circ 42'$$

**COMP.** Mn or Mg may proxy for Ca in part.

<sup>44</sup> M. Perutz: *Mineral. Mag.*, XXIV, 573 (1937).

<sup>45</sup> E. P. Henderson and J. J. Glass: *Am. Mineral.*, XXI, 273 (1936).

<sup>46</sup> N. L. Bowen: *J. Wash. Acad. Sci.*, XXIII, 87 (1933). M. A. Peacock: *Zeit. Krist.*, XC, 97 (1935).  $a$  and  $b$  are not here interchanged to make  $b > a$  because in doing so the relation with wollastonite would be lost.



STRUC.<sup>47</sup> Space group  $P\bar{1}$ ;  $a$  7.91,  $b$  7.08,  $c$  7.05 Å. U.C. 2.

PHYS. CHAR. Crystals often elongated along  $a$ ; twinning on 010. Perfect 100 and 001 cleavages.  $H. = 4.5-5$ .  $G. = 2.74-2.88$ .  $F. = 2$ . Attacked by HCl.

OPT. PROP. The optic plane and  $Z$  are nearly normal to 010, but  $Z \wedge b = 13^\circ$ ;  $X \wedge c = 10^\circ$  ( $19^\circ$ —Palache<sup>48</sup>), nearly in the plane of the acute angle  $\beta$ . See Fig. 351.

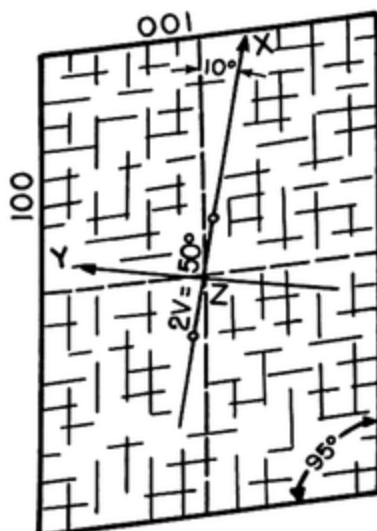


FIG. 351. Approximate optic orientation of pectolite.

More accurately,<sup>49</sup> for  $X$ ,  $\phi = -115^\circ$ ,  $\rho = 11^\circ$ ; for  $Y$ ,  $\phi = 78^\circ$ ,  $\rho = 80^\circ$ ; for  $Z$ ,  $\phi = -13^\circ$ ,  $\rho = 88^\circ$ . Elongation positive. Optic data follow:

	(Fe,Mn)O <sup>50</sup>	(+) $2V$	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$
Utonai <sup>51</sup>	0.10	?	1.595	1.604	1.632	0.037
Franklin <sup>48</sup>	3.86	Mod.	1.604	1.610	1.636	0.032
Paterson <sup>49</sup>	1.12	$50^\circ$	1.600	1.605	1.636	0.036
Kola <sup>52</sup>	1.50	$53^\circ 34'$	1.610	1.614	1.642	0.032

Colorless or white.

Pectolite with 5% MgO has<sup>53</sup>  $G. = 2.69$ ; the optic plane is parallel to the fibers, which have negative elongation.  $(+) $2V$  = ?$ ,  $N_Y = 1.56$  ca.  $N_Z - N_X = 0.04$  ca. Very rare.

OCCUR. Pectolite is found in cavities or seams in igneous or metamorphic rocks often associated with zeolites, as at Bergen Hill, New Jersey.

ALTER. It alters to *stevensite* [ $H_2Mg_3(SiO_3)_4 \cdot H_2O$ ], which is isotropic (apparently amorphous) with  $N = 1.50$  ca.

<sup>47</sup> B. E. Warren and J. Biscoe: *Zeit. Krist.*, LXXX, 391 (1931). M. A. Peacock: *Zeit. Krist.*, XC, 97 (1935).

<sup>48</sup> C. Palache: *U. S. Geol. Surv. Prof. Paper* 180 (1935).

<sup>49</sup> M. A. Peacock: *Zeit. Krist.*, XC, 97 (1935).

<sup>50</sup> Including  $Fe_2O_3$ .

<sup>51</sup> Z. Harada: *Min. Abst.*, VI, 92 (1935).

<sup>52</sup> E. E. Kostyleva: *Min. Abst.*, III, 111 (1926).

<sup>53</sup> E. Reuning: *Cent. Min.*, 1907, 739.

**DIAG.** It is distinguished from wollastonite by positive elongation and stronger birefringence.

**SCHIZOLITE**

TRICLINIC PINACOIDAL(?)

 $\text{HNa}(\text{Ca}, \text{Mn})_2\text{Si}_3\text{O}_9$  $a:b:c = 0.900:1:0.871$  $\alpha = 95^\circ 22'$  $\beta = 90^\circ (11' ?)$  $\gamma = 101^\circ 56'$ 

**COMP.** Mn may exceed Ca; Fe, Ce, K may be present. Schizolite is probably a manganpectolite, but a continuous series is not yet known.

**STRUC.**<sup>54</sup> Near that of pectolite;  $a$  7.24,  $b$  8.09,  $c$  7.05 Å.

**PHYS. CHAR.** Crystals like those of pectolite; perfect 100 and 001 cleavages.  $H. = 5-5.5$ .  $G. = 2.97-3.13$ .

**OPT. PROP.** The axis  $Z$  is near  $a$ ;  $Y \wedge b = 9^\circ$ . Elongation  $\pm$ .  $(+)2E = 82^\circ 40'$ ,  $r < v$  distinct.  $N_X = 1.631$ ,  $N_Y = 1.636$ ,  $N_Z = 1.660$ ,  $N_Z - N_X = 0.029$ . Again:<sup>55</sup>  $(+)2V = 51^\circ$ ,  $N_X = 1.633$  calc.,  $N_Y = 1.641$ ,  $N_Z = 1.677$ ,  $N_Z - N_X = 0.044$  (calc.). Color light red, altering to brown.

**OCCUR.** Found in nepheline syenite, as in Greenland.

**Margarosanite**<sup>56</sup> ( $\text{Ca}_2\text{PbSi}_3\text{O}_9$ ) is triclinic with  $a:b:c = 0.750:1:1.285$ ,  $\alpha = 74^\circ 37'$ ,  $\beta = 129^\circ 29'$ ,  $\gamma = 101^\circ 5'$ . Crystals lamellar to acicular with perfect 010 cleavage; two other cleavages nearly normal to 010 make angles of  $78^\circ$  and  $102^\circ$ .  $H. = 2.5-3$ .  $G. = 3.99$ .  $F. = 2$  in R. F.; about 6 in O. F. In 010 tablets  $X' \wedge$  cleavages  $= 44^\circ$  and  $34^\circ$ ; in these tablets  $N_{Z'} = 1.795$ ,  $N_{X'} = 1.73$ .  $(-)2V = 83^\circ$ ,  $r < v$ .  $N_X = 1.729$ ,  $N_Y = 1.773$ ,  $N_Z = 1.807$ ,  $N_Z - N_X = 0.078$ . Colorless to white. A very similar mineral<sup>57</sup> from Sweden has three cleavages, one (010) perfect, and one (001) good.  $G. = 4.39$ .  $Z \wedge c = 8^\circ 40'$  in acute angle  $\beta$ . Margarosanite is found at Franklin, New Jersey, with almandite, willemite, etc.

**Babingtonite** ( $\text{HCa}_2\text{Fe}''\text{Fe}'''\text{Si}_5\text{O}_{15}$ ) is triclinic pinacoidal<sup>58</sup> with  $a:b:c = 0.642:1:0.575$ ,  $\alpha = 91^\circ 31'$ ,  $\beta = 93^\circ 51'$ ,  $\gamma = 104^\circ 4'$ . Space group  $P\bar{1}$ ;  $a$  7.36,  $b$  11.52,  $c$  6.58 Å. U.C. 2. Structurally related to rhodonite. Crystals short prisms with perfect 001 and poor  $1\bar{1}0$  cleavages.  $H. = 5.5-6$ .  $G. = 3.36$ .  $F. = 3$  to black magnetic glass. Insoluble in acids. The optic plane is nearly parallel with  $1\bar{1}0$  and nearly normal to 001; extinction is at  $44^\circ$  on  $1\bar{1}1$ , at  $31^\circ$  on  $1\bar{1}1$ , and at about  $40^\circ$  on  $1\bar{1}0$ . For  $X$ ,  $\phi = -104^\circ$ ,  $\rho = 46^\circ$ ; for  $Y$ ,  $\phi = 145^\circ$ ,  $\rho = 70^\circ$ ; for  $Z$ ,  $\phi = 39^\circ$ ,  $\rho = 51^\circ$ . Marked dispersion.<sup>58</sup>  $(+)2V = 76^\circ$ ,  $r > v$  strong,  $N_X = 1.720$ ,  $N_Y = 1.731$ ,  $N_Z = 1.753$ ,  $N_Z - N_X = 0.033$ . Again:  $(+)2V = 60^\circ-65^\circ$ ,  $N_X = 1.713$ ,  $N_Y = 1.726$ ,  $N_Z = 1.746$ ,  $N_Z - N_X = 0.033$ .

Color greenish to brownish black in mass; in thin section  $X$  = dark emerald to bluish green,  $Y$  = pale violet-brown or lilac,  $Z$  = dark to pale brown or grass green. Babingtonite is found in cavities in granite, gneiss, etc., associated with epidote and garnet as in Passaic County, New Jersey; also in Bessemer slags. It is characterized by its triclinic symmetry and strong pleochroism.

<sup>54</sup> T. Ito: *Zeit. Krist.*, C, 437 (1939).  $a$  and  $b$  interchanged to make  $b > a > c$ .

<sup>55</sup> V. I. Gerasimovsky: *Min. Abst.*, VII, 210 (1938).

<sup>56</sup> W. E. Ford and W. M. Bradley: *Am. Jour. Sci.*, CXCII, 159 (1916).

<sup>57</sup> G. Flink: *Geol. För. Förh.*, 1917, 426.

<sup>58</sup> W. E. Richmond: *Am. Mineral.*, XXII, 630 (1937).

## 2. Tetragonal rings<sup>59</sup> with type formula $A_m(B_4X_{12})_n$

**Joaquinite**<sup>60</sup>  $[NaBa(Ti,Fe)_3O_3Si_4O_{12}]$  is orthorhombic with  $a:b:c = 0.919:1:2.14$ ;  $a$  9.61,  $b$  10.45,  $c$  22.4 Å. U.C. 4. Crystals {001} tablets or equant.  $H. = 5.5$ .  $G. = 3.89$ . The optic plane is 010;  $Z = c$ .  $(+ )2V = 50^\circ$  ca.,  $r < v$ .  $N_X = 1.748$ ,  $N_Y = 1.767$ ,  $N_Z = 1.823$ ,  $N_Z - N_X = 0.075$ . Color honey yellow to brown; absorption  $X < Y < Z$ . Found with benitoite and neptunite in San Benito County, California.

**Kainosite**<sup>61</sup>  $[Ca_2(Ce,Y)_2CO_3Si_4O_{12} \cdot H_2O]$  is orthorhombic dipyramidal with  $a:b:c = 0.876:1:0.464$ . Crystals short prismatic with one good cleavage.  $H. = 5.5$ .  $G. = 3.34-3.61$ .  $F. = 6$ . Soluble in HCl. The optic plane is 010;  $Z = a$ .  $(- )2V = 39^\circ 45'$ ,  $N_X = 1.664$ ,  $N_Y = 1.689$ ,  $N_Z = 1.691$ ,  $N_Z - N_X = 0.027$  (Graham<sup>62</sup>).  $N_X = 1.667$ ,  $N_Y = 1.681$ ,  $N_Z = 1.683$ ,  $N_Z - N_X = 0.016$  (Larsen<sup>23</sup>).  $N_Z = 1.683$ ,  $N_Z - N_X = 0.05$  (Schetelig<sup>63</sup>). Color pink or yellow to chestnut brown; not pleochroic. Found in ore or veins, as at Nordmark, Sweden, and North Burgess, Ontario.

**Neptunite**  $[Na_2(Fe,Mn)TiSi_4O_{12}]$  is monoclinic prismatic<sup>64</sup> with  $a:b:c = 1.316:1:0.801$ ,  $\beta = 115^\circ 24'$ . Space group  $C2/m$  or  $C2/c$ ;  $a$  16.54,  $b$  12.64,  $c$  10.04 Å. U.C. 8. Crystals prismatic, varied, with perfect 110 cleavages at  $80^\circ$ .  $H. = 5-6$ .  $G. = 3.19$ .  $F. = 2.5$  to a black globule. Insoluble in HCl.  $Y = b$ ;  $Z \wedge c = -20^\circ$ .  $(+ )2V = 49^\circ$ ,  $r < v$ , extreme.  $N_X = 1.690$ ,  $N_Y = 1.700$ ,  $N_Z = 1.736$ ,  $N_Z - N_X = 0.046$ . Again:<sup>65</sup>  $(+ )2V = 36^\circ$ ,  $N_X = 1.6908$ ,  $N_Y = 1.6927$ ,  $N_Z = 1.7194$ ,  $N_Z - N_X = 0.0286$ . Color black; deep red in splinters.  $X =$  pale yellow,  $Y =$  orange or yellowish red,  $Z =$  deep ochre yellow, bright orange, or brownish red. Found in nepheline syenite in the Kola region, U. S. S. R.

## 3. Hexagonal or ditrigonal rings with type formula $A_m(B_6X_{18})_n$

**BERYL**<sup>66</sup>      DIHEXAGONAL DIPYRAMIDAL       $c/a = 0.9956$        $Be_3Al_2Si_6O_{18}$

**COMP.** The formula is simplified; other elements often present in small amount include Na, K, Li, Cs, H.

**STRUC.** Space group  $C6/mcc$ ;  $a$  9.21,  $c$  9.17 Å. U.C. 2.

**PHYS. CHAR.** Crystals prismatic (see Fig. 352) with poor 0001 cleavage.  $H. = 7.5-8$ .  $G. = 2.65-2.9$ .  $F. = 1420^\circ$  ca. Insoluble in acids.

<sup>59</sup> No silicates are known to have tetragonal ring structures; those given are reasonably supposed to have such structures.

<sup>60</sup> C. Palache and W. F. Foshag: *Am. Mineral.*, XVII, 308 (1932).

<sup>61</sup> Also called *cenosite*.

<sup>62</sup> R. P. D. Graham and H. V. Ellsworth: *Am. Mineral.*, XV, 205 (1930).

<sup>63</sup> J. Schetelig: *Vid.-Selsk. Skr.*, I, Mat. Nat. Kl., No. 1, 124 (1922).

<sup>64</sup> B. Gossner and F. Mussgnug: *Cent. Min.*, 1928A, 274. *Strukber.*, I, 791 (1931). Perhaps neptunite is a tectosilicate.

<sup>65</sup> G. T. Kravchenko: *Min. Abst.*, VII, 211 (1938).

<sup>66</sup> Beryl is clearly a tectosilicate; it can be considered a cyclosilicate only by regarding  $BeO_4$  tetrahedrons as not the equivalents of  $SiO_4$  tetrahedrons; this seems desirable since the hexagonal  $SiO_4$  rings are so important.

**OPT. PROP.** Uniaxial negative, but some crystals have a very small optic angle ( $2E$  up to  $10^\circ$ ); in such cases the hexagonal form is due to twinning of three or six orthorhombic units as in aragonite. In cross sections the center of such twins may be uniaxial. Refrindex, birefringence, and density vary considerably with the tenor of alkalis, which reaches a maximum of at least 7 per cent. The range of known values follows:  $N_O = 1.568-1.602$ ,  $N_E = 1.564-1.595$ ,  $N_O - N_E = 0.004-0.008$ .

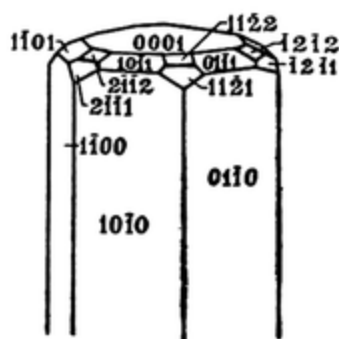


FIG. 352. A crystal habit of beryl.

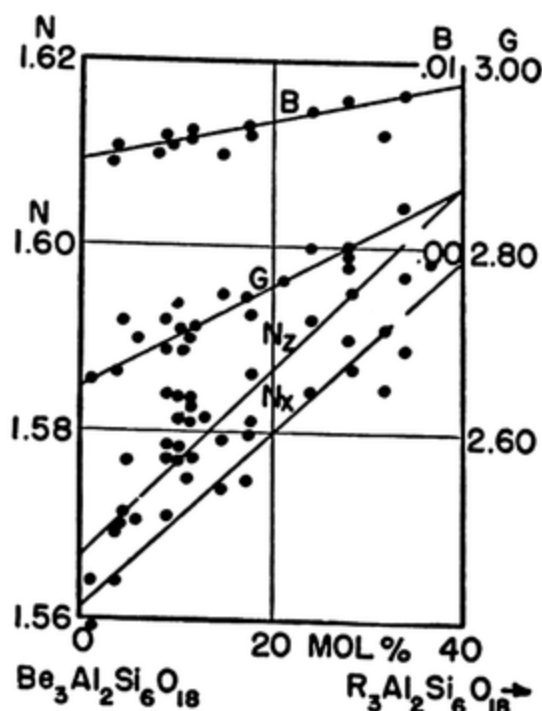


FIG. 353. Properties of beryl.

The relations between properties and composition are shown approximately in Fig. 353.

Color green, blue, yellow, white, pink; the beryl with much alkali, especially cesium, is usually pink. Luster vitreous, sometimes resinous. Colorless in thin section; more or less pleochroic in thick sections as follows:

Emerald	Blue Beryl	Yellow Beryl	Pink Beryl
O = Yellowish green	Greenish blue to colorless	Golden yellow	Colorless
E = Sea green	Blue	Reddish yellow	Pale pink

Sometimes the absorption is  $O > E$ .

**ALTER.** Beryl alters rather easily to kaolin, the change beginning in fractures and making the mineral opaque and soft.

**OCCUR.** It is found in pegmatites, in tin lodes, and in mica schists, as near Muso, Colombia; Ekaterinburg, Siberia; San Mateo, Brazil; Grafton, New Hampshire; Haddam, Connecticut.

**DIAG.** Beryl differs from apatite in its lower refringence, and slightly stronger birefringence; also in thick sections, in its pleochroism. It is harder than apatite and insoluble in acids. It has higher relief than nepheline.

## TOURMALINE

$XY_3Al_6(OH)_4(BO_3)_3Si_6O_{18}$ , with  $X = Na, Ca$ , rarely  $K$ ;  $Y = Mg, Al, Li, Fe$ , etc.

DITRIGONAL PYRAMIDAL <sup>67</sup>  $c/a = 0.447$

COMP. Tourmaline varies widely in composition; the formula <sup>68</sup> is still uncertain; it is approximately  $H_4NaMg_3Al_6B_3Si_6O_{31}$  for *dravite*,  $H_4NaFe_3Al_6B_3Si_6O_{31}$  for *schorlite*,  $H_8Na_2Li_3Al_{15}B_6Si_{12}O_{62}$  for *elbaite*,  $H_4NaMn_3Al_6B_3Si_6O_{31}$  for *tsilaisite*,  $H_4CaMg_4Al_5B_3Si_6O_{31}$  for *uvite*; tourmaline may contain some  $Cr, Fe'''$ ,  $K$ . There is a continuous series from dravite to schorlite (and to uvite) and also from schorlite to elbaite, but none is known from dravite to elbaite. As in other silicates,  $Al_2$  may proxy for  $MgSi$  (at least to a limited extent).

STRUC. Space group <sup>67</sup>  $R3m$ ;  $a$  15.81 to 16.01; <sup>69</sup>  $c$  7.10 to 7.22 Å. Hexagonal U.C. contains  $3(Na,Ca)R_3Al_6(O,OH)_4Si_6B_3O_{27}$ .

PHYS. CHAR. Crystals usually prismatic, vertically elongated and striated; also lenticular; some crystals show distinct hemimorphism. Radiating groups common. Twinning rare. Difficult  $11\bar{2}0$  and  $10\bar{1}1$  cleavages.  $H. = 7-7.5$ .  $G. = 2.9-3.2$ . Dravite fuses at about 4 and schorlite at about 5.5, but elbaite is infusible. After fusion gelatinizes with  $HCl$ . Insoluble even in  $HF$ .

OPT. PROP. Uniaxial and negative, but (under strain?) may be slightly biaxial,  $2E$  reaching about  $10^\circ$ . Refrindex moderate and birefringence moderate to strong. Schorlite has higher relief and stronger birefringence than dravite or elbaite. Data follow. See also Figs. 354-356.

		Schorlite			Dravite	
Average <sup>70</sup>		Approximate Range			Average <sup>70</sup>	Range
All		Black	Blue	Green		
$N_O = 1.668$		1.65 -1.69	1.652-1.665	1.64 -1.67	1.650	1.63 -1.655
$N_E = 1.639$		1.63 -1.66	1.628-1.637	1.62 -1.65	1.628	1.61 -1.63
$N_O - N_E = 0.029$		0.025-0.035	0.024-0.030	0.026-0.034	0.022	0.022-0.025
$G. =$			3.14 -3.21	3.12 -3.22		3.03 -3.10

		Elbaite		Special Types with	
Average <sup>70</sup>		Range		$Cr_2O_3 = 10.86$	$Fe_2O_3 = 6.68$
$N_O = 1.646$		1.635-1.65		1.687	1.692
$N_E = 1.625$		1.615-1.63		1.641	1.657
$N_O - N_E = 0.021$		0.015-0.023		0.046	0.035
$G. =$		3.01 -3.13		3.12	3.2

The relations between composition and properties in the two chief tourmaline series are shown in Fig. 354. These two series can usually be distinguished from each other by color (brown, or less commonly

<sup>67</sup> G. E. Hamburger and M. J. Buerger: *Am. Mineral.*, XXXIII, 532 (1948).

<sup>68</sup> E. Gübelin: *Schw. Min. Pet. Mit.*, XIX, 325 (1939).

<sup>69</sup> F. Machatschki: *Zeit. Krist.*, LXX, 211, and LXXI, 45 (1929).

<sup>70</sup> P. Reiner: *Inaug. Diss. Heidelberg*, 1913, 49. C. Doelter: *Hdb. Mineralchemie*, II, 2, 782 (1917).





blue or green to black in the dravite-schorlite series and black to delicate tints of green, pink, yellow, etc., in the schorlite-elbaite series) and also by the presence or absence of lithium compounds in the associated minerals. The relations between composition and properties in the dravite-uvite series are shown in Fig. 355. The Na-Ca variation is entirely independent of the MgFe-LiAl variation. The relations

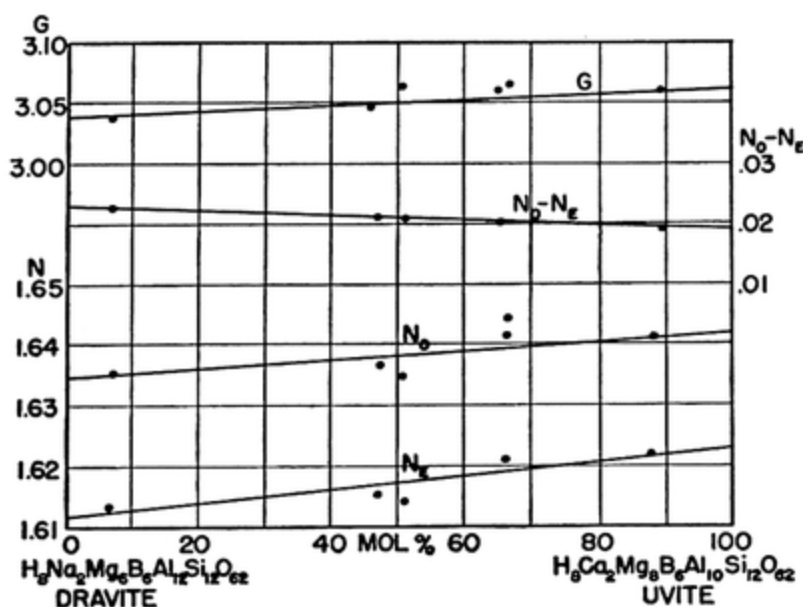


FIG. 355. Properties of the dravite-uvite series.

between composition and properties in the entire uvite-dravite-schorlite-elbaite system are shown in Fig. 356.

Color black, bluish black, dark brown, less commonly blue, green, red, pink, colorless. A single crystal may vary in color; it may have different colors in zones or irregularly distributed or at opposite ends of the vertical axis. Pleochroism quite variable in intensity, but the absorption is always  $O > E$ . Therefore the maximum absorption occurs when the vertical axis (and elongation) is at right angles to the vibration plane of the polarizer. See Figs. 357 and 358. Examples of pleochroic formulas follow:

	O(Z)	E(X)
Sections 1.5 mm. thick		
Elbaite	Pink, pale green, greenish blue	Colorless or nearly so
Dravite	Dark yellowish brown	Pale yellow
Sections 0.03 mm. thick		
Elbaite	Colorless, pink, pale blue	Colorless
Dravite	Pale yellow	Colorless
Schorlite	Yellowish brown to black	Pale to dark yellow
Schorlite	Dark green	Reddish violet, brownish
Schorlite	Blue of various shades	Pale violet-green, yellowish
Cr-tourmaline	Green to bluish green	Yellow

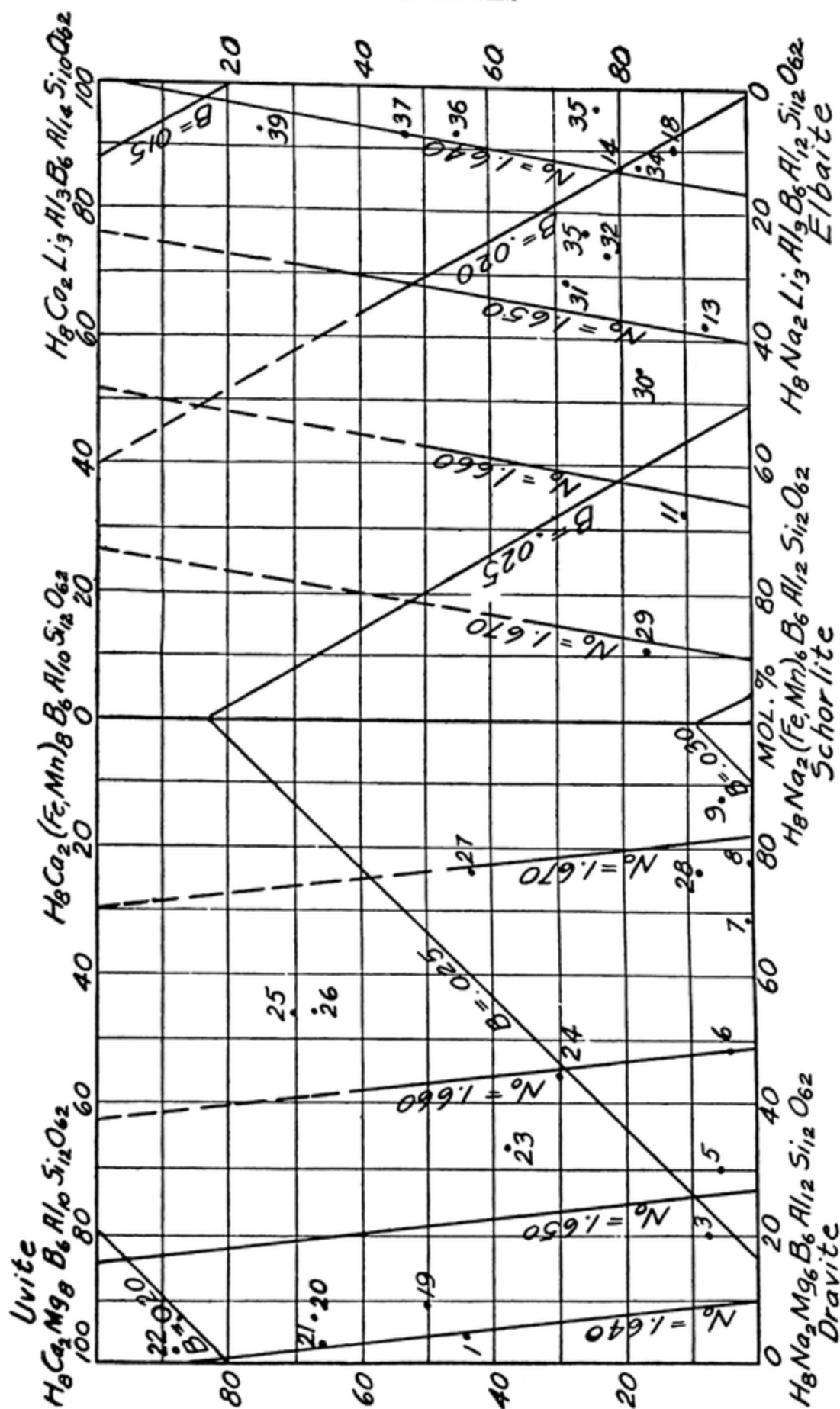
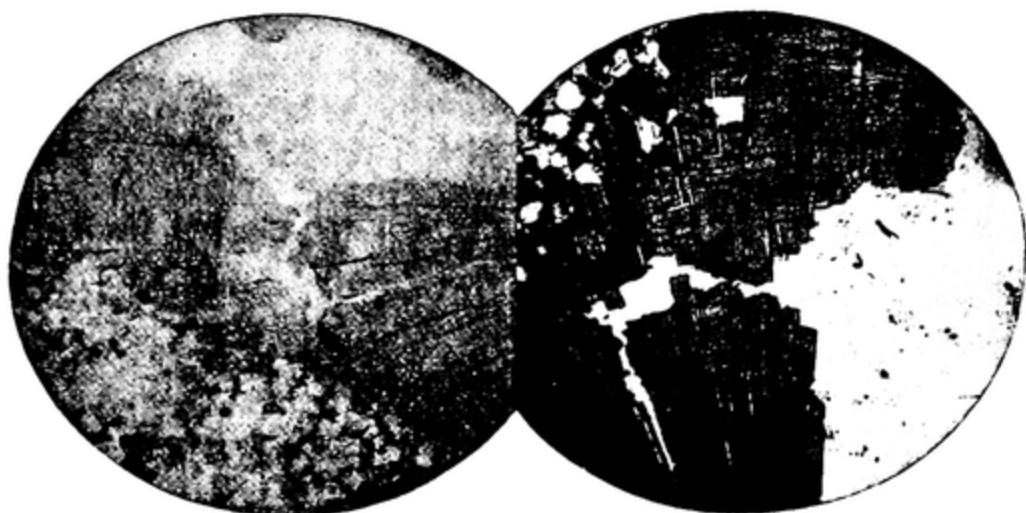


FIG. 356. Properties of the tourmaline system.

**INCL.** Very intense pleochroic colors may be present about inclusions of zircon or rutile; the halos often differ from the enclosing mineral, and disappear upon heating; in them the birefringence is increased.



FIGS. 357, 358. Photomicrographs of tourmaline showing its strong absorption.

**ALTER.** Usually unaltered, but may change to sericite, often with biotite and sometimes with chlorite.

**OCCUR.** Tourmaline is widely, but rather sparsely, distributed in schists, gneisses, slates, etc. It is a common product of fumarolic action,

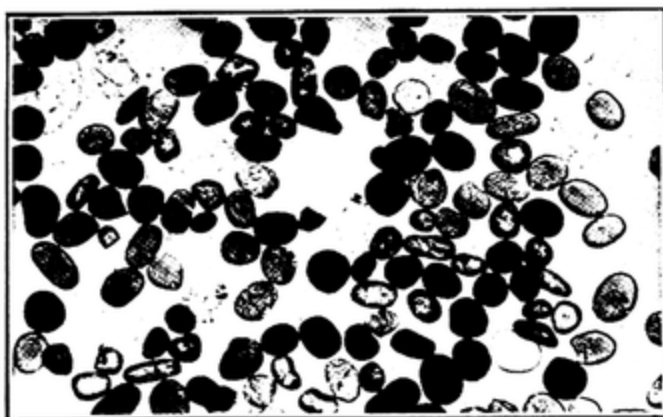


FIG. 359. Tourmaline in heavy residues from sediments. Photomicrograph by Mrs. F. C. Edson.

and common in some pegmatites. It is apparently primary in some igneous rocks. In sediments it is usually well rounded and flattened, as shown in Fig. 359.

**DIAG.** Tourmaline is readily distinguished by its marked pleochroism with maximum absorption normal to the elongation; also by its form, lack of cleavage, distinct relief, and bright interference colors.

**CORDIERITE**<sup>71</sup> (*Iolite*)

ORTHORHOMBIC DIPYRAMIDAL

$a:b:c = 0.568:1:0.549$

**COMP.** Cordierite varies in composition not only in the tenor of Mg and Fe, but also in containing excess  $\text{SiO}_2$  (up to  $\text{Mg}_2\text{Al}_4\text{Si}_6\text{O}_{20}$ ?) and some alkalis and  $\text{H}_2\text{O}$  (perhaps in cavities or channels in the crystal structure parallel to  $c$ ).

**STRUC.** Space group<sup>72</sup> *Cccm*;  $a$  9.67,  $b$  17.03,  $c$  9.35 Å. U.C. 4.

**PHYS. CHAR.** Crystals short prismatic with large base (see Fig. 360); aragonite type of pseudohexagonal twinning common on 110 or 130; see Figs. 361, 363, 364, and 366. Also may show multiple twinning.

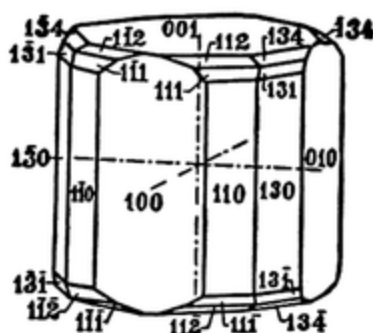


FIG. 360. A crystal habit of cordierite.

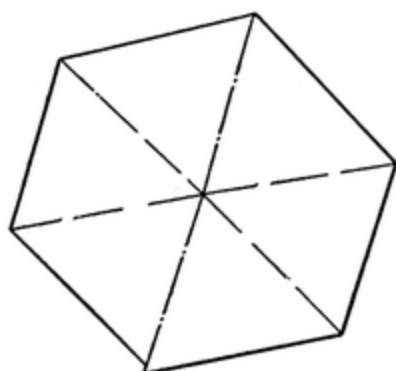
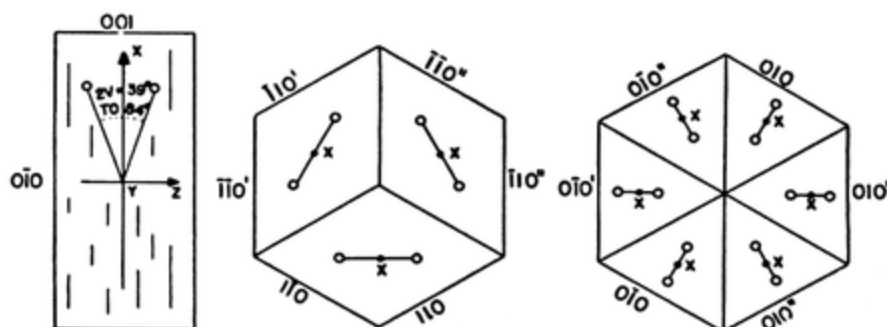


FIG. 361. Pseudohexagonal cyclic twinning in cordierite.

Distinct 010 and poor 100 and 001 cleavages. When partially altered the mineral becomes lamellar parallel to 001.  $H. = 7-7.5$ .  $G. = 2.57-2.66$ . Dissociates at about  $1450^\circ$ . Partly decomposed by acids.

**OPT. PROP.** The optic plane is 100;  $X$  is normal to 001 (see Fig. 362);



FIGS. 362-364. The optic orientation in a simple crystal and in twins of cordierite.

<sup>71</sup> Like beryl, cordierite is a tectosilicate, but its structure is very similar to that of beryl.

<sup>72</sup> A. Byström: *Min. Abst.*, VIII, 369, 1943.  $a$  and  $b$  interchanged to make  $b > a > c$ .

the optic angle is quite variable, usually negative, but varies through  $90^\circ$  so some samples are positive; it may even vary notably in different parts of a single crystal. Heat increases the optic angle considerably. Dispersion weak with  $r < v$ . Most cordierite has:  $(- )2V = 40^\circ\text{--}80^\circ$ ,  $N_X = 1.538 \pm 0.005$ ,  $N_Y = 1.543 \pm 0.005$ ,  $N_Z = 1.545 \pm 0.005$ ,  $N_Z - N_X = 0.008 \pm 0.002$ . The known limits of variation are:  $2V$  over

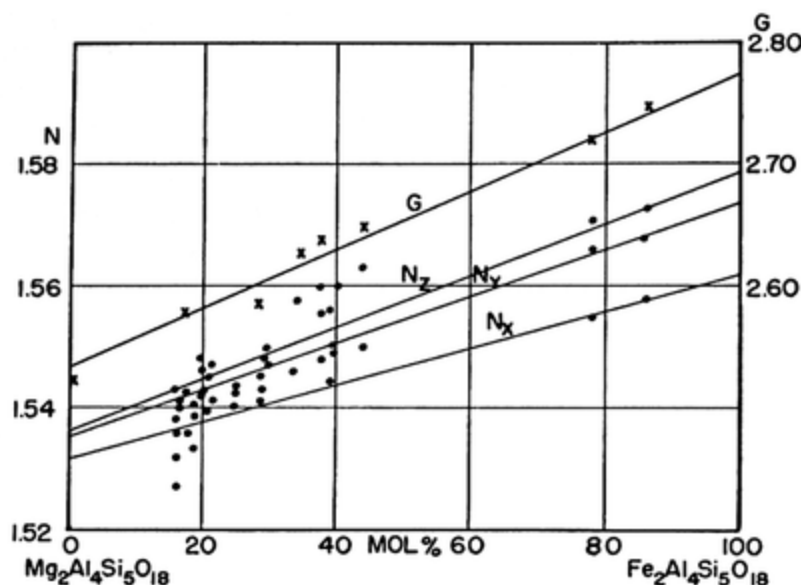


FIG. 365. Properties of cordierite.

$X = 39^\circ\text{--}99^\circ$ ,  $N_X = 1.522^{73}\text{--}1.558$ ,  $N_Y = 1.532\text{--}1.568$ ,  $N_Z = 1.527\text{--}1.573$ ,  $N_Z - N_X = 0.006\text{--}0.015$ .

The refractive indices, birefringence, and specific gravity all increase with increase of Fe, as shown in Fig. 365, but the variations in optic angle<sup>74</sup> from  $(- )2V$  near  $0^\circ$  to  $(+ )2V$  near  $0^\circ$  cannot at present be explained satisfactorily by variations in composition, though several attempts to do so have been made.<sup>75</sup>

Color of natural cordierite is light to dark blue, smoky blue; rarely, greenish, yellow, brown. Color and pleochroism usually absent in thin section, but in thick plates:

X = clear yellow, green, brown, or reddish.

Y = dark violet, dark blue, green, dark brown.

Z = clear blue of various shades, yellow, brown.

But cordierite rich in iron has X = colorless, Y and Z violet even in thin section.

<sup>73</sup> S. J. Shand: *Am. Mineral.*, XXVIII, 391 (1943).

<sup>74</sup> S. Tsuboi: *Jap. Jour. Geol. Geog.*, XIII, 333 (1936).

<sup>75</sup> See H. Shibata: *Jap. Jour. Geol. Geog.*, XIII, 205 (1936), A. N. Winchell: *Am. Mineral.*, XXII, 1175 (1937), and R. E. Folinsbee: *Am. Mineral.*, XXVI, 485 (1941).

**INCL.** Cordierite of the plutonic rocks often contains inclusions of sillimanite, spinel, staurolite, zircon, apatite, dumortierite. The last three are often surrounded by pleochroic halos which may be visible even in colorless cordierite. In these halos the color parallel to X is changed to deep lemon yellow, the refringence is slightly increased, and, unlike halos in other minerals, the birefringence is decreased. The halos disappear at red heat.

Cordierite of the volcanic rocks contains many vitreous inclusions of secondary origin accompanied by octahedrons of spinel, magnetite, etc.

Cordierite in schists at granite contacts often contains carbonaceous inclusions, regularly distributed, as in andalusite.

**ALTER.** Cordierite alters very readily, giving rise to many products of varied aspect, which have received many names. These secondary products consist of biotite, muscovite, chlorite, and isotropic substances. Cordierite when altered chiefly to mica with development of basal lamination is called *gigantolite*; if the lamination is lacking the name *pinite* is applied. Similarly, when the alteration product is chiefly chlorite it is

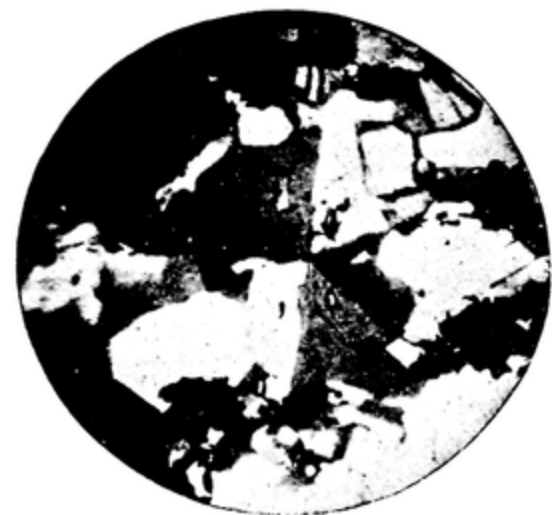


FIG. 366. Photomicrograph of cordierite in thin section, showing pseudo-hexagonal twinning.

called *chlorophyllite* when the basal lamination is present, and *prasiolite* when it is lacking.

**OCCUR.** Cordierite is found in gneiss, in schists and slates, in modified igneous rock, especially granite, and in rock inclusions in volcanic rocks. It is also found in (endomorphosed?) igneous rocks rich in alumina and magnesia and with more than the feldspar ratio of silica. It is usually associated with quartz, orthoclase, albite, tourmaline, andalusite, sillimanite, staurolite, spinel, garnet, zircon, etc.

**DIAG.** Cordierite is distinguished in thin section from quartz and orthoclase by inclusions (of sillimanite, staurolite, etc.), by pleochroic halos about zircon or dumortierite, and by the mode of formation of alteration products. Furthermore, the refringence is (nearly always) distinctly higher than that of orthoclase, and quartz is uniaxial. Pleochroism and pleochroic halos are characteristic, if present. However, the most satisfactory diagnostic is the symmetrical extinction in cyclic twins at  $30^\circ$  from the twinning plane, with all parts of the twin perpendicular to the negative acute bisectrix (basal section). See Fig. 366.



## E. SOROSILICATES (GROUPS)

1. Type formula  $A_m(B_2X_7)_n$ 

## (a) WITHOUT ADDITIONAL ANIONS—ANHYDROUS

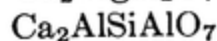
## MELILITE

TETRAGONAL SCALENOHEDRAL<sup>1</sup>  $c/a = 0.65$  ca.

## Åkermanite



## Gehlenite



## Hardystonite



COMP. Besides the end-members given above,  $Ca_2MnSi_2O_7$  and  $Ca_2Fe''Si_2O_7$  are important in some components of slags, and  $Ca_2Fe'''_2SiO_7$  and  $Ca_3Al_2Si_4O_{14}$  are probable minor components of some natural crystals.  $NaCaAlSi_2O_7$  forms crystal solutions<sup>2</sup> up to 30 per cent with  $Ca_2Al_2SiO_7$ , but not with  $Ca_2MgSi_2O_7$ .

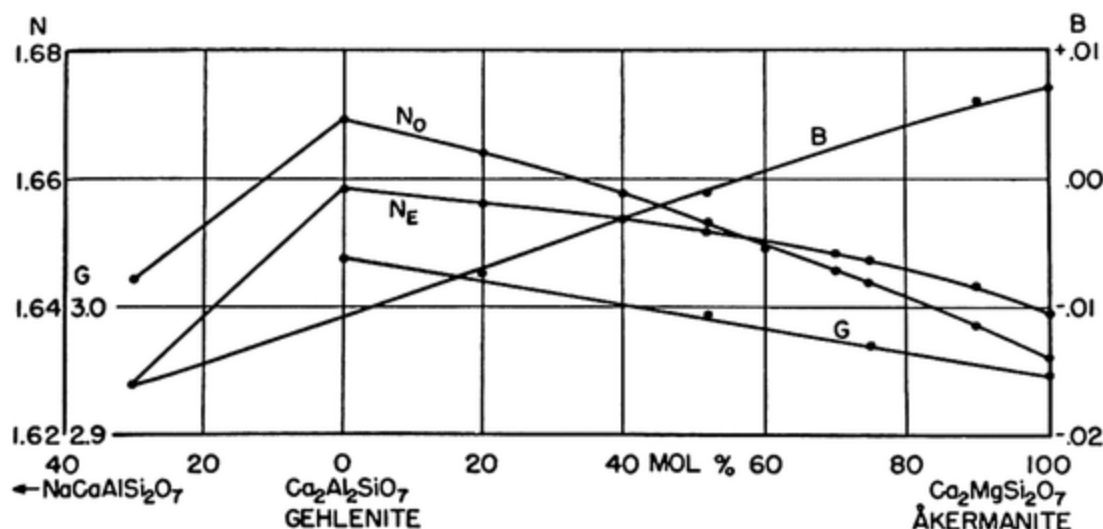


FIG. 367. Properties of the gehlenite-åkermanite series and also of gehlenite with some  $NaCaAlSi_2O_7$ . From data of J. R. Goldsmith: personal communication, Jan. 7, 1948.

STRUC. Space group <sup>2</sup>  $P\bar{4}2_1m$ ;  $a$  7.69,  $c$  5.10 Å for artificial  $Ca_2Al_2SiO_7$ . U.C. 2.  $a$  7.73,  $c$  5.01 Å for natural crystal.<sup>3</sup>  $a$  7.83,  $c$  4.99 Å for artificial <sup>4</sup>  $Ca_2ZnSi_2O_7$ .

PHYS. CHAR. Crystals short prismatic with poor 001 cleavage. H. = 5–6. G. = 2.95 ( $Ca_2MgSi_2O_7$ ) to 3.04 ( $Ca_2Al_2SiO_7$ ) and to 3.2 with some Fe. F. = 1500° ca. Gelatinizes with HCl.

<sup>1</sup> F. Raaz: *Min. Abst.*, V, 28 (1932).

<sup>2</sup> J. R. Goldsmith: *Jour. Geol.*, LVI, 437 (1948).

<sup>3</sup> B. E. Warren: *Zeit. Krist.*, LXXIV, 131 (1930).

<sup>4</sup> B. E. Warren and O. R. Trautz: *Zeit. Krist.*, LXXV, 525 (1930).

OPT. PROP. Uniaxial, positive (åkermanite) to negative (gehlenite) and isotropic at about 40%  $\text{Ca}_2\text{Al}_2\text{SiO}_7$ —see Fig. 367, which is based on artificial compounds and shows also the effect of  $\text{NaCaAlSi}_2\text{O}_7$  on gehlenite. The properties of the gehlenite-hardystonite series are given in Fig. 368, those of the åkermanite-gehlenite-ferroåkermanite system in

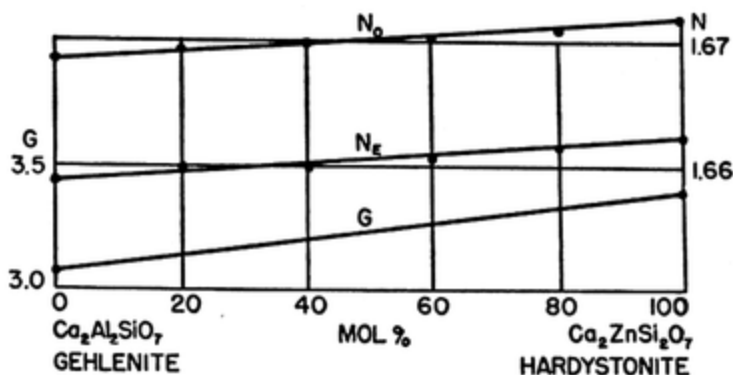


FIG. 368. Properties of the gehlenite-hardystonite series.

Fig. 369, and those <sup>5</sup> of the åkermanite-gehlenite-hardystonite system in Fig. 370. Natural crystals practically always vary some from this system because they usually contain some Na, K,  $\text{Fe}'''$ , Mn, H, excess Ca, etc. Data follow:

	$N_o$	$N_e$	$N_o - N_e$	G.	N (glass)
Gehlenite <sup>6</sup> (artificial)	1.669	1.658	-0.011	3.038	1.638
Åkermanite <sup>6</sup> (artificial)	1.632	1.639	+0.007	2.944	1.641
Ferroåkermanite <sup>7</sup> (artificial)	1.690	1.673	-0.013	3.23	
Hardystonite <sup>5</sup> (artificial)	1.6718	1.6624	-0.0094	3.40	
Hardystonite <sup>8</sup> (natural)	1.6758 Li	1.6647	-0.0111		
Justite (Fe,Zn,Mn)	1.670	1.657	-0.013		
Ferrigehlenite <sup>9</sup>	1.666	1.661	-0.005 (with 7.76 $\text{Fe}_2\text{O}_3$ and 5.66 $\text{Al}_2\text{O}_3$ )		
70 Gehlenite <sup>4,5</sup> + 30 $\text{NaCaAlSi}_2\text{O}_7$ (artificial)	1.644	1.628	-0.016		

Colorless, grayish green, brown; colorless in thin section.

OCCUR. Melilite is found in contact zones and ores. Also in basic volcanic rocks, as on the island of Oahu, Hawaii. Also found in slags and artificial melts.

<sup>5</sup> R. B. McCormick: unpublished Ph. D. Thesis, Univ. Wis., 1936.

<sup>6</sup> J. B. Ferguson and A. F. Buddington: *Am. Jour. Sci.*, CC, 131 (1920).

<sup>7</sup> J. F. Schairer: *Am. Mineral.*, XXIX, 90 (1944).

<sup>8</sup> C. Palache: personal communication; anal. 1 of *U. S. Geol. Surv. Prof. Paper* 180.

<sup>9</sup> A. F. Buddington: *Am. Jour. Sci.*, CCI, 35 (1922).

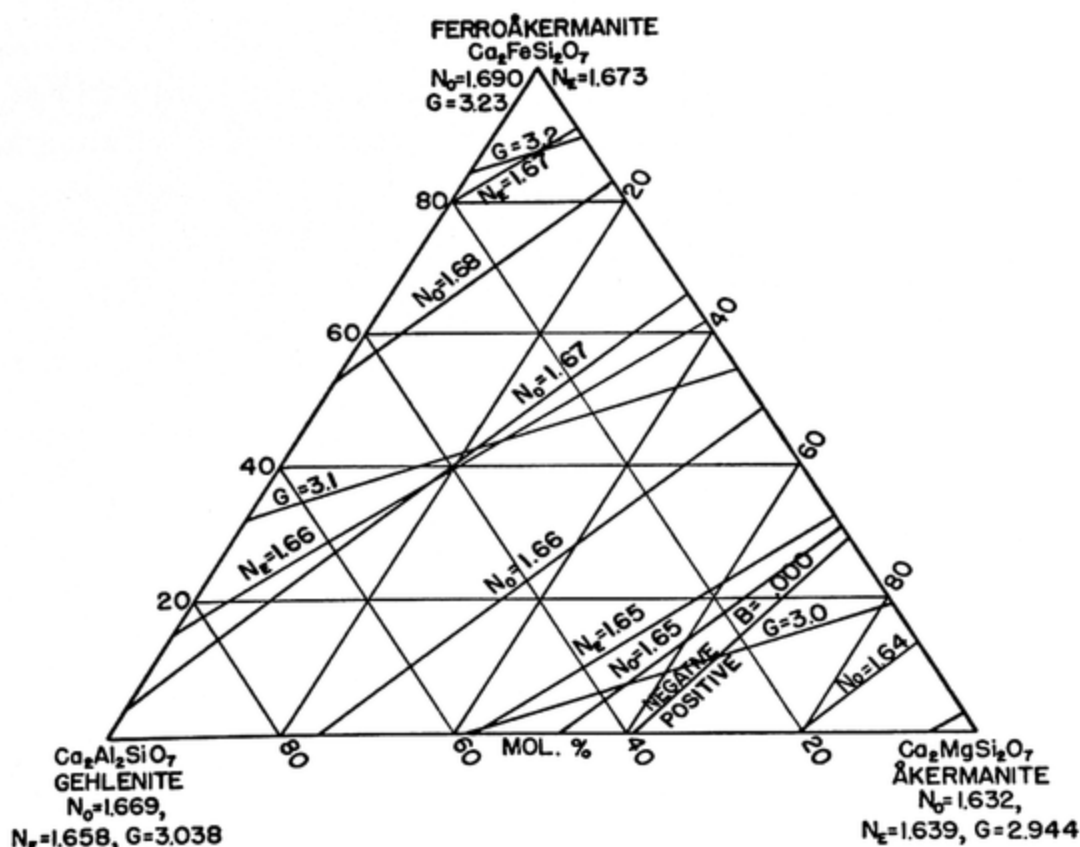


FIG. 369. Properties of the gehlenite-åkermanite-ferroåkermanite system.

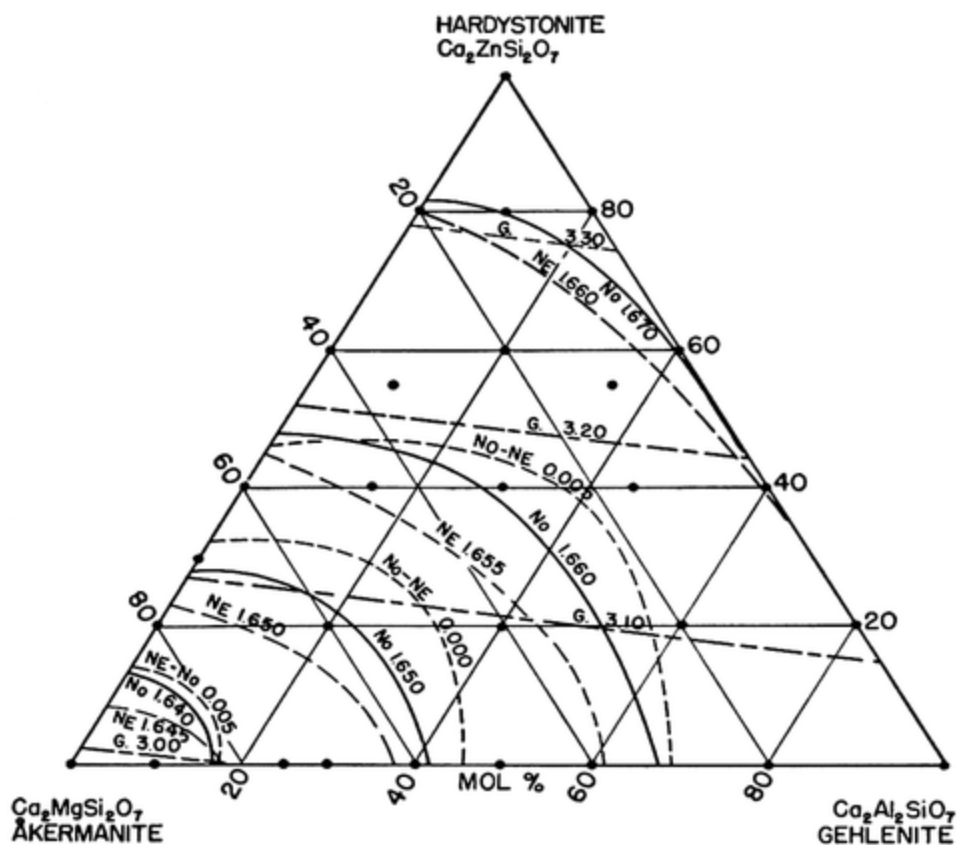


FIG. 370. Properties of the gehlenite-åkermanite-hardystonite system.

**DIAG.** It resembles vesuvianite and zoisite, but zoisite is biaxial positive and vesuvianite has higher refringence and weaker birefringence.

**Meliphanite**<sup>10</sup>  $[(Ca,Na)_2Be(Si,Al)_2(O,F)_7]$  is tetragonal scalenohedral with  $c/a = 0.933$ .  $a$  10.58,  $c$  9.88 Å. U.C. 8. Crystals obtuse pyramidal; also platy, with distinct 001 cleavage. H. = 5–5.5. G. = 3.0. Fuses with intumescence. Insoluble. Uniaxial negative with  $N_O = 1.6126$ ,  $N_E = 1.5934$ ,  $N_O - N_E = 0.0192$ . Sometimes  $(- )2E = 36^\circ$  (max.). Color yellow; rarely reddish from alteration. In thick plates O = honey to brownish yellow, E = greenish yellow, and  $O > E$ . Found in pegmatite near Fredricksvårn, Norway.

**Barysilite**<sup>11</sup>  $(Pb_3Si_2O_7)$  is rhombohedral with  $c/a = 0.486$ . Crystals rhombohedral in basal tablets with distinct 0001 cleavage. H. = 3. G. = 6.72. F. = 2.5. Gelatinizes with  $HNO_3$ . Uniaxial negative with  $N_O = 2.033$ ,  $N_E = 2.015$ ,  $N_O - N_E = 0.018$ . Colorless. Found in ore deposits as at Långban, Sweden.

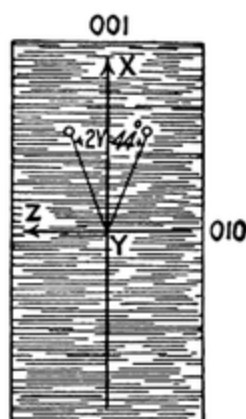


FIG. 371. The optical orientation of leucophanite.

**Bazzite**<sup>11a</sup> is a silicate of scandium, etc., chemically related to thortveitite. It is hexagonal and barrel-shaped. H. = 6.5. G. = 2.8. F. = 7, but turns dark. Insoluble except in HF. Uniaxial negative with  $N_O = 1.626$ ,  $N_E = 1.608$ ,  $N_O - N_E = 0.018$  in the interior, and  $N_O = 1.623$ ,  $N_E = 1.602$ ,  $N_O - N_E = 0.021$  in the outer zone. Color bright azure blue with O = very pale greenish yellow, E = intense azure blue. Found in a geode in granite in Italy.

**Leucophanite**  $[(Ca,Na)_2BeSi_2(O,OH,F)_7]$  is orthorhombic and pseudotetragonal<sup>10</sup> with  $a:b:c = 1:1:1.349$ ;  $a$  7.38,  $b$  7.38,  $c$  9.96 Å. U.C. 4. Crystals {001} tablets with perfect 001 and 010 cleavages. Twinning frequent on 110 or 001, often interpenetrated. H. = 4. G. = 2.96. F. = 6, with intumescence. Insoluble. The optic plane is 100; X = c. See Fig.

371.  $(- )2V = 39^\circ$ ,  $r > v$ .  $N_X = 1.571$ ,  $N_Y = 1.595$ ,  $N_Z = 1.598$ ,  $N_Z - N_X = 0.027$ . Color white, green, yellow; colorless in section. Found in pegmatite on the island of Låven, Norway.

**Barylite**<sup>12</sup>  $(BaBe_2Si_2O_7)$  is orthorhombic dipyramidal with<sup>13</sup>  $a:b:c = 0.843:1:0.399$ . Space group probably  $Pnma$ ;  $a$  9.79,  $b$  11.61,  $c$  4.63 Å. U.C. 4. Crystals prismatic or tabular with good 001 and 100 and poor 010 cleavages. H. = 7. G. = 4. F. = 7. Insoluble. The optic plane is 001; X = b.  $(+ )2V = 65^\circ$ ,  $r > v$  weak;  $N_X = 1.681$ ,  $N_Y = 1.685$ ,  $N_Z = 1.695$ ,  $N_Z - N_X = 0.014$  (Weibull<sup>14</sup>);  $(+ )2V = 81^\circ$ ,  $N_X = 1.691$ ,  $N_Y = 1.696$ ,  $N_Z = 1.703$ ,  $N_Z - N_X = 0.012$  (Aminoff<sup>12</sup>);  $(- )2V = 70^\circ$ ,  $N_X = 1.695$ ,  $N_Y = 1.702$ ,  $N_Z = 1.708$ ,  $N_Z - N_X = 0.013$  (Berman<sup>15</sup>). Color milk white. Found in limestone in Sweden and at Franklin, New Jersey.

<sup>10</sup> W. H. Zachariasen: *Norsk Geol. Tidsk.*, XII, 577 (1931).

<sup>11</sup> E. V. Shannon and H. Berman: *Am. Mineral.*, XI, 130 (1926); L. H. Bauer and H. Berman: *Am. Mineral.*, XV, 340 (1930).

<sup>11a</sup> E. Artini: *Min. Abst.*, I, 204 (1921).

<sup>12</sup> G. Aminoff: *Geol. För. Förh.*, XLV, 124 (1923).

<sup>13</sup> E. R. Ygberg: *Geol. För. Förh.*, LXIII, 394 (1942).

<sup>14</sup> M. Weibull: *Geol. För. Förh.*, XXII, 33 (1900).

<sup>15</sup> In C. Palache and L. H. Bauer: *Am. Mineral.*, XV, 30 (1930).

**Rankinite**<sup>16</sup> ( $Ca_3Si_2O_7$ ) is monoclinic with no cleavage.<sup>17</sup>  $H. = 5.5$ .  $G. = 2.86$ . Gelatinizes with HCl.  $X \wedge a = 15^\circ$ ,  $Y = b$ .  $(+)2V = 64^\circ$ ,  $N_X = 1.641$ ,  $N_Y = 1.644$ ,  $N_Z = 1.650$ ,  $N_Z - N_X = 0.009$ . Alters easily to afwillite ( $Ca_3Si_2O_7 \cdot 3H_2O$ ). Found with melilite, larnite, and wollastonite at Scawt Hill, England.

**Thortveitite**<sup>18</sup>  $[(Sc,Y)_2Si_2O_7]$  is monoclinic prismatic with  $a:b:c = 0.767:1:0.552$ ,  $\beta = 103^\circ 8'$ . Space group<sup>19</sup>  $C2/m$ ;  $a$  6.56,  $b$  8.58,  $c$  4.74 Å. U.C. 2. Crystals tapering, with good 110 cleavage and 001 parting; twinning on 110.  $H. = 6-7$ .  $G. = 3.58$ .  $F. = \text{diff.}$  Insoluble in HCl.  $X \wedge c = -5^\circ$ ;  $Y = b$ .  $(-)2V = 65^\circ \text{ ca.}$ ,  $r > v$ .  $N_X = 1.751$ ,  $N_Y = 1.789$ ,  $N_Z = 1.803$ ,  $N_Z - N_X = 0.052$ . Color grayish green; pleochroic in thick sections with  $X = \text{deep green}$ ,  $Y$  and  $Z = \text{yellow}$ . Found in pegmatite in Norway and Madagascar.

**Thalenite**<sup>20</sup> ( $Y_2Si_2O_7$ ) is monoclinic with  $a:b:c = 0.919:1:0.648$ ,  $\beta = 97^\circ 5'$ . Crystals {100} tablets or prismatic, with no cleavage.  $H. = 6.5$ .  $G. = 4.23-4.45$ .  $Z = b$ ,  $Y \wedge c = +1^\circ$  to  $+3^\circ$ .  $(-)2V = 67^\circ 35'$  ( $73^\circ$ ,  $r < v$  weak, Vogt<sup>21</sup>).  $N_X = 1.7312$ ,  $N_Y = 1.7375$ ,  $N_Z = 1.7436$ ,  $N_Z - N_X = 0.0124$ . Crystals may be zoned with  $N_Z - N_X$  as low as 0.007 in the central part. Color pink. Found in pegmatite in Sweden.

**Ytttrialite**<sup>22,23</sup>  $[(Y,Th)_2Si_2O_7?]$  is closely related to thalenite, but contains Th, U, Ce, Al, etc. It is prismatic.  $H. = 5.5-6.5$ .  $G. = 4.3-4.6$ . Isotropic with  $N = 1.751-1.758$ . Color black, brown, olive green; pale green in section. Found in pegmatite at Barringer Hill, Texas, and Iisaka, Japan.

**Enigmatite**<sup>24</sup>  $[Na_4Fe''Fe'''Ti_2(Si_2O_7)_6?]$  varies much in composition usually containing some K, Ca, Mg, Mn, Al, etc. It is triclinic<sup>25</sup> with  $a:b:c = 1.00:1:0.585$ ,  $\alpha = 97^\circ 2'$ ,  $\beta = 96^\circ 49'$ ,  $\gamma = 112^\circ 26'$ .  $a$  18.3,  $b$  18.3,  $c$  10.6 Å. Crystals vertically elongated. Perfect 010 and 100 cleavages. Common twinning on  $\bar{1}10$ , sometimes lamellar.  $H. = 5.5$ .  $G. = 3.74-3.85$ .  $F. = 3$ . Partly decomposed by acids. The optic plane is nearly parallel with 010;  $Z \wedge c = \text{about } 45^\circ$  in 010 (see Fig. 372);  $Z' \wedge c$  in 100 is about  $4^\circ$ . Maximum extinction angle in the vertical zone is  $38^\circ$  (Bowen<sup>27</sup>).  $(+)2V = 32^\circ$ ,  $N_X = 1.81$ ,  $N_Y = 1.82$ ,  $N_Z = 1.88$ ,  $N_Z - N_X = 0.07$ . Also reported<sup>28</sup> as  $N_Z - N_X = 0.004$ . Color black; streak reddish brown; intensely pleochroic in section with  $X < Y < Z$  and  $X = \text{clear reddish brown}$ ,  $Y = \text{dark}$

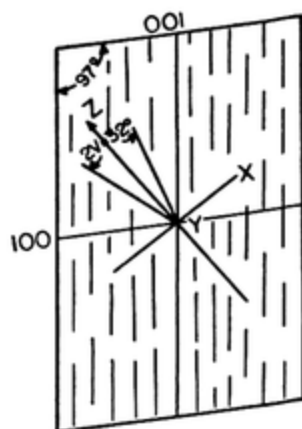


FIG. 372. The optic orientation of enigmatite.

<sup>16</sup> C. E. Tilley: *Mineral. Mag.*, XXVI, 190 (1942).

<sup>17</sup> S. G. Gordon found good 100 cleavage—*Am. Mineral.*, VIII, 110 (1923).

<sup>18</sup> J. P. Marble and J. J. Glass: *Am. Mineral.*, XXVII, 696 (1942).

<sup>19</sup> B. Gossner and F. Mussgnug: *Cent. Min.*, 1929A, 1.

<sup>20</sup> T. Vogt: *Min. Abst.*, II, 25 (1923).

<sup>21</sup> J. H. L. Vogt: *Vid. Skr.*, Mat. nat. Kl., No. 1, 19 (1922).

<sup>22</sup> W. E. Hidden and J. B. Mackintosh: *Am. Jour. Sci.*, CXXXVIII, 477 (1889).

<sup>23</sup> S. Hata: *Min. Abst.*, VII, 356 (1939).

<sup>24</sup> M. Fleischer: *Am. Jour. Sci.*, CCXXXII, 343 (1936).

<sup>25</sup> C. Palache: *Zeit. Krist.*, LXXXVI, 280 (1933).

<sup>26</sup> B. Gossner and F. Mussgnug: *Cent. Mineral.*, 1929A, 5.

<sup>27</sup> N. L. Bowen: *Am. Mineral.*, XXII, 139 (1937).

<sup>28</sup> W. Kunitz: *N. Jahrb. Min.*, Bl. Bd. LXX, A, 399 (1936).

chestnut brown, Z = very dark brown. Found in nepheline syenites, etc., as in Kenya, Africa, and Pantelleria.

**Rhönite**<sup>29</sup> is perhaps enigmatite with some NaSi replaced by CaAl. Crystal habit like hornblende; twinning on 010.  $G. = 3.6$  ca. Streak red-brown. Optic plane inclined to 010. Extinction angle on 010 about  $40^\circ$  in the acute angle  $\beta$ . Refrindex and birefringence about as in brown hornblende. Strongly pleochroic with X = brown, sometimes greenish, Y = brown, Z = dark red-brown to black. Found in the Rhön district in Germany.

### (a) WITHOUT ADDITIONAL ANIONS—HYDROUS

**Foshallassite**<sup>30</sup> ( $\text{Ca}_3\text{Si}_2\text{O}_7 \cdot 3\text{H}_2\text{O}$ ?) is probably orthorhombic with perfect tabular cleavage. It has the same composition as afwillite.  $H. = 2.5-3$ .  $G. = 2.5$ . X normal to cleavage.  $(-)2V = 12^\circ-18^\circ$ ,  $N_X = 1.535$ ,  $N_Y = 1.542$ ,  $N_Z = 1.549$ ,  $N_Z - N_Y = 0.014$ . Again,  $N_Z - N_X = 0.018$ . Found in veins with calcite and mesolite at Yukspor Mountain, U.S.S.R.

**Afwillite**<sup>31</sup> ( $\text{Ca}_3\text{Si}_2\text{O}_7 \cdot 3\text{H}_2\text{O}$ ) is monoclinic sphenoidal<sup>32</sup> with  $a:b:c = 2.097:1:2.381$ ,  $\beta = 98^\circ 26'$ . Space group  $P2_1$ ;  $a$  11.39,  $b$  5.47,  $c$  13.09 Å. U.C. 4. Crystals elongated along  $b$  with perfect 001 and poor 100 cleavages.  $H. = 4$ .  $G. = 2.63$ .  $F. = 6$ . Soluble in HCl. The optic plane is 010;  $X \wedge c = -31.2^\circ$  red,  $-30^\circ$  Na,  $-29.9^\circ$  blue.  $(+)2V = 54^\circ 40'$ ,  $r < v$ .  $N_X = 1.6169$ ,  $N_Y = 1.6204$ ,  $N_Z = 1.6336$ ,  $N_Z - N_X = 0.0167$ . Colorless. Found in a diamond mine in South Africa.

### (b) WITH ADDITIONAL ANIONS—ANHYDROUS

**Rowlandite**<sup>33</sup>  $[\text{Fe}''(\text{Y,Ce,Lu})_4\text{F}_2(\text{Si}_2\text{O}_7)_2]$  is isotropic and has conchoidal fracture; crystals are unknown.  $H. = 6-7$ .  $G. = 4.5$ .  $F. = 7$ . Gelatinizes with HCl.  $N = 1.725$ . Color drab green to red (altered); pale green in thin section. Found with gadolinite in Llano County, Texas.

#### GANOMALITE

HEXAGONAL

$(\text{Ca,Pb})_{10}(\text{OH,Cl})_2(\text{Si}_2\text{O}_7)_3$

$c/a = 1.3167$

COMP. A complete series from the OH to the Cl compound is very probable but not yet fully proved. The Cl end-member has been called *nasonite*.

<sup>29</sup> J. Soellner: *N. Jahrb. Min.*, Bl. Bd. XXIV, 475 (1907); M. Fleischer: *Am. Jour. Sci.*, XXXII, 343 (1936).

<sup>30</sup> P. Tschirwinsky: *Min. Abst.*, VII, 10 (1938).

<sup>31</sup> J. Parry and F. E. Wright: *Mineral. Mag.*, XX, 277 (1925).

<sup>32</sup> C. Gottfried: *Zeit. Krist.*, LXXXIV, 172 (1933).

<sup>33</sup> W. E. Hidden: *Am. Jour. Sci.*, CXLII, 430 (1891).



**PHYS. CHAR.** Crystals hexagonal prisms with basal and prismatic cleavages.  $H. = 3$  (OH end-member); 4 (nasonite).  $G. = 5.7$  (OH); 5.43 (Cl).  $F. = \text{easy}$ . Gelatinizes with HCl.

**OPT. PROP.** Uniaxial positive; also biaxial with small 2V. Data somewhat inconsistent, as follows:

OH Dominant		Nasonite	
Larsen <sup>34</sup>	Zenzén <sup>35</sup>	Larsen <sup>34</sup>	Aminoff <sup>36</sup>
$N_O = 1.910$		1.917	1.9453 Na
$N_E = 1.945$		1.927	1.9710
$N_E - N_O = 0.035$	0.009–0.050	0.010	0.0263

**OCCUR.** Ganomalite has been found at Långban, Sweden; nasonite is found at Franklin, New Jersey.

**Molybdophyllite** <sup>37</sup>  $[Pb_2Mg_2(OH)_2Si_2O_7]$  is hexagonal (trigonal) with  $c/a = 0.549$ . Crystals foliated with perfect 0001 cleavage.  $H. = 3-4$ .  $G. = 4.72$ . Uniaxial negative with  $N_O = 1.815$ ,  $N_E = 1.761$ ,  $N_O - N_E = 0.054$ . Pale green in mass; colorless in section. Found with hausmannite at Långban, Sweden.

**Bertrandite** <sup>38</sup>  $[Be_4(OH)_2Si_2O_7]$  is orthorhombic pyramidal with  $a:b:c = 0.571:1:0.298$ . Space group <sup>39</sup>  $Cmc$ ;  $a$  8.67,  $b$  15.19,  $c$  4.53 Å. U.C. 4. Crystals {001} or {010} plates of varied habit. Perfect 001 and good 010 and 110 cleavages. Common twinning on 011 or 021.  $H. = 6$ .  $G. = 2.6$ .  $F. = 7$ . Insoluble.  $X = a$ ;  $Y = b$ . See Fig. 373.  $(- )2V = 75^\circ$  ca.,  $N_X = 1.589$ ,  $N_Y = 1.602$ ,  $N_Z = 1.613$ ,  $N_Z - N_X = 0.024$ . Colorless, with vitreous luster; pearly on 001. Found in pegmatite with beryl, hercynite, tourmaline, quartz, etc., as in Chaffee County, Colorado. Bertrandite differs from muscovite and some zeolites in that the best cleavage is normal to the obtuse bisectrix, and this cleavage has negative elongation and parallel extinction; the crystal forms (hemimorphic) and pearly luster are also distinctive.

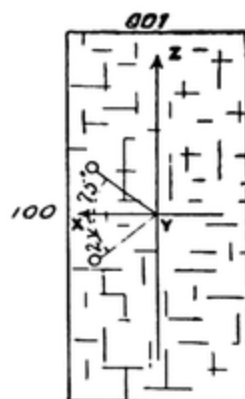


FIG. 373. The optical orientation of bertrandite.

**Harstigitite**  $[Be_2Ca_3Si_3O_{11}]$  is orthorhombic with  $a:b:c = 0.715:1:1.015$ . Crystals short prismatic without cleavage.  $H. = 5.5$ .  $G. = 3.05$ .  $X = c$ ;  $Y = b$ .  $(+)2V = 52^\circ$ ,  $r < v$  weak.  $N_X = 1.678$ ,  $N_Y = 1.68$ ,  $N_Z = 1.683$ ,  $N_Z - N_X = 0.005$ . Colorless. Found with garnet in ore at the Harstig mine, Sweden.

**Grothine** <sup>40</sup> is a silicate of Al and Ca with a little Fe, probably related to harstigitite. It is orthorhombic with  $a:b:c = 0.458:1:0.848$ .  $G. = 3.09$ .  $F. = 7$ . Attacked by  $H_2SO_4$ .  $X = b$ ;  $Y = c$ .  $(+)2V = \text{medium}$ ,  $r < v$ .  $N_Y = 1.554$ ,  $N_Z - N_X = 0.016$ . Colorless. Found in a contact zone near Naples, Italy.

<sup>34</sup> E. S. Larsen: *U. S. Geol. Surv. Bull.* 679 (1921).

<sup>35</sup> N. Zenzén: *Geol. För. Förh.*, XXXVII, 294 (1915), and XXXVIII, 477 (1916).

<sup>36</sup> G. Aminoff: *Geol. För. Förh.*, XXXVIII, 473 (1916).

<sup>37</sup> G. Flink: *Bull. Geol. Inst. Upsala*, V, 41 (1901).

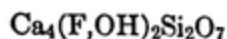
<sup>38</sup> G. Switzer: *Am. Mineral.*, XXIV, 791 (1939).

<sup>39</sup> T. Ito and J. West: *Zeit. Krist.*, LXXXIII, 384 (1932);  $a$  and  $b$  interchanged to make  $b > a$ , and to agree with the setting of Penfield and others, whose  $c$  must be halved.

<sup>40</sup> F. Zambonini: *Min. Abst.*, I, 107 (1921).

## CUSPIDINE

## MONOCLINIC



$$a:b:c = 0.724:1:1.934 \quad \beta = 90^\circ 38'$$

COMP. With much OH the mineral has been called *custerite*.

PHYS. CHAR. Crystals small, pseudorhombic, with very good 001 cleavage. Distinct 110 cleavages in custerite, with the three directions nearly at right angles. Lamellar twinning. H. = 5-6. G. = 2.95 *ca.* F. = diff. Soluble in  $\text{HNO}_3$ .

OPT. PROP. Biaxial positive with large optic angle and  $r > v$  marked.  $Y = b$  (Y reported as parallel to 010 in custerite). Marked inclined dispersion.

	2E	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$	$Z \wedge c$	COLOR
Cuspidine <sup>41</sup>	113°	1.592	1.595	1.606	0.014	6°	
Cuspidine <sup>42</sup>	110°	1.590	1.595	1.602	0.012	5.5°	Rose-red to colorless
Custerite <sup>43</sup>	105°	1.586	1.59	1.598	0.012	6.5°	Greenish gray to colorless

OCCUR. Cuspidine is found in contact zones with garnet, etc.; also produced artificially; <sup>41</sup> also found at Vesuvius.

DIAG. Cuspidine has moderate relief and birefringence, lamellar twinning and a small extinction angle, marked dispersion, and very good basal cleavage.

**Murmanite** <sup>44</sup> [ $\text{Na}_2\text{Ti}_2(\text{OH})_4\text{Si}_2\text{O}_7$ ?] is of uncertain formula, containing variable  $\text{TiO}_2$  and some  $\text{ZrO}_2$ ,  $\text{Cb}_2\text{O}_6$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{MnO}$ ,  $\text{CaO}$ , etc. It is monoclinic; tabular with perfect 100 cleavage and two other cleavages. H. = 2-3. G. = 2.84; (2.77). F. = 7. Soluble in  $\text{H}_2\text{SO}_4$ . X nearly normal to 100; Y nearly normal to 001.  $(- )2V = 64^\circ$ ,  $r < v$ .  $N_X = 1.735$ ,  $N_Y = 1.765$ ,  $N_Z = 1.839$ ,  $N_Z - N_X = 0.104$ . Color violet on fresh cleavage. Luster metallic. Bronze tarnish. Streak cherry red. Pleochroic with X = pink, Y = clear brown, Z = dark brown. Found in nepheline syenite of the Kola peninsula, U.S.S.R.

**Tilleyite** <sup>45</sup> [ $\text{Ca}_5(\text{CO}_3)_2\text{Si}_2\text{O}_7$ ] is monoclinic with perfect 100 cleavage, one good cleavage (101?) normal to 010 and at  $+54^\circ$  to the perfect cleavage, and a poor cleavage ( $\bar{1}01$ ?) normal to 010 and at  $-50^\circ$  to the perfect cleavage. Twinning on 101. G. = 2.84. The optic plane is 010;  $X \wedge c = 18^\circ$ ,  $(+)2V = \text{nearly } 90^\circ$ ,  $r < v$ ;  $N_X = 1.617$ ,  $N_Y = 1.635$ ,  $N_Z = 1.652$ ,  $N_Z - N_X = 0.035$  (Larsen <sup>46</sup>). Again:  $Z \wedge c = 12^\circ$ ,  $N_X = 1.612$ ,  $N_Y = 1.632$ ,  $N_Z = 1.653$ ,  $N_Z - N_X = 0.041$  (Nockolds <sup>46</sup>). Colorless. Found in a contact zone at Crestmore, California, and at Carlingford, Ireland.

**Astrophyllite** <sup>47</sup> [ $(\text{K,Na})_2(\text{Fe,Mn})_4(\text{Ti,Zr})(\text{OH,F})_2(\text{Si}_2\text{O}_7)_2$ ] is pseudo-orthorhombic with  $a:b:c = 0.555:1:0.256$ . Probably triclinic (or monoclinic?) with  $\alpha$ ,  $\beta$ ,  $\gamma$  very near  $90^\circ$ .  $a$  11.70,  $b$  21.10,  $c$  5.40 Å. U.C. 4. Crystals elongated along  $a$ .

<sup>41</sup> V. V. Lapin: *Min. Abst.*, IX, 11 (1944). Artificial crystals.

<sup>42</sup> F. Starrabba: *N. Jahrb. Min.*, I, 366 (1914).

<sup>43</sup> Umpleby, Schaller, and Larsen: *Am. Jour. Sci.*, CLXXXVI, 385 (1913). See also C. E. Tilley: *Mineral. Mag.*, XXVIII, 90 (1947).

<sup>44</sup> A. E. Fersman: *Min. Abst.*, II, 263 (1924); III, 236 (1927); M. N. Gutkova: *Min. Abst.*, V, 198 (1933).

<sup>45</sup> E. S. Larsen and K. C. Dunham: *Am. Mineral.*, XVIII, 469 (1933).

<sup>46</sup> S. R. Nockolds: *Mineral. Mag.*, XXVIII, 151 (1947). C. E. Tilley: *Min. Abst.*, X, 285 (1948).

<sup>47</sup> B. Gossner and E. Reindl: *Cent. Mineral.*, 1934A, 161;  $b$  and  $c$  interchanged to make  $b > a > c$ ;  $\gamma$  is about  $94^\circ$ .

Perfect 010 and poor 100 cleavages; laminae brittle.  $H. = 3$ .  $G. = 3.3-3.4$ .  $F. = 3$  with swelling. Decomposed by HCl leaving scaly silica.  $Y = a$ ;  $Z = c$ . See Fig. 374.  $(+)2V = 75^\circ$  ca.,  $r > v$ .  $[(-)2V = 88^\circ - \text{Böggild}^{48}]$   $N_X = 1.678$ ,  $N_Y = 1.703$ ,  $N_Z = 1.733$ ,  $N_Z - N_X = 0.055$ . Also:  $^{49} (+)2V = 80^\circ$ ,  $N_X = 1.740$ ,  $N_Y = 1.746$ ,  $N_Z = 1.765$ ,  $N_Z - N_X = 0.025$ . Again:  $^{50} (+)2V = 70^\circ-74^\circ$ ,  $N_X = 1.691$ ,  $N_Y = 1.705$ ,  $N_Z = 1.738$ ,  $N_Z - N_X = 0.045$ . Color bronze to gold yellow. Luster submetallic, pearly. Strongly pleochroic with  $X > Y > Z$  and  $X =$  dark golden yellow, reddish brown,  $Y =$  orange-yellow, yellowish brown,  $Z =$  lemon yellow, paler yellowish brown. Found in nepheline syenite and soda granite, as at Narsarsuk, Greenland, and Pikes Peak, Colorado. Differs from mica in having brittle laminae with the obtuse bisectrix normal to the cleavage and maximum absorption normal to the laminae.

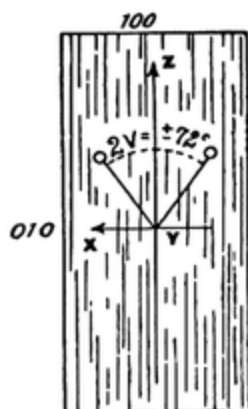


FIG. 374. Approximate optic orientation of astrophyllite.

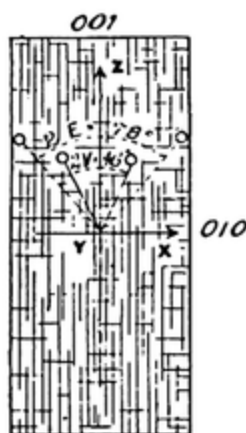


FIG. 375. The optic orientation of hemimorphite.

## (b) WITH ADDITIONAL ANIONS—HYDROUS

**Aminoffite** <sup>51</sup>  $[\text{Ca}_3\text{Be}_3\text{Al}(\text{OH})_3\text{Si}_8\text{O}_{28} \cdot 4\text{H}_2\text{O}]$  is ditetragonal dipyramidal with  $c/a = 0.7116$ . Space group  $I4/mmm$ ;  $a$  13.8,  $c$  9.8 Å. U.C. 3. Poor 001 cleavage.  $H. = 5.5$ .  $G. = 2.94$ .  $F. = 7$ . Insoluble. Uniaxial (also biaxial) and negative with  $N_O = 1.647$ ,  $N_E = 1.637$ ,  $N_O - N_E = 0.010$ . Found in veins and cavities at Långban, Sweden.

**HEMIMORPHITE** (*Calamine*) ORTHORHOMBIC PYRAMIDAL  $\text{Zn}_4(\text{OH})_2\text{Si}_2\text{O}_7 \cdot \text{H}_2\text{O}$   
 $a:b:c$  <sup>52</sup> = 0.783:1:0.478

STRUC. Space group <sup>52</sup>  $Imm$ ;  $a$  8.38,  $b$  10.70,  $c$  5.11 Å. U.C. 4.

PHYS. CHAR. Crystals distinctly hemimorphic when doubly terminated. Often in sheaflike aggregates. Perfect 110 and poor 101 cleavages. Rare twinning on 001.  $H. = 5$ .  $G. = 3.45$ .  $F. = 6$  with bright light. Gelatinizes with HCl.

<sup>48</sup> O. B. Böggild: *N. Jahrb. Min.*, I, 362 (1910).

<sup>49</sup> B. Gossner and F. Mussgnug: *Cent. Mineral.*, 1931A, 419.

<sup>50</sup> E. Bohnstedt: *Min. Abst.*, V, 232 (1933).

<sup>51</sup> C. S. Hurlbut: *Geol. För. Förh.*, LIX, 290 (1937).

<sup>52</sup> T. Ito and J. West: *Zeit. Krist.*, LXXXIII, 1 (1932).

**OPT. PROP.** The optic plane<sup>53</sup> is 100;  $Z = c$ . See Fig. 375.  $(+)2V = 46^\circ$ ,  $r > v$  strong.  $N_X = 1.614$ ,  $N_Y = 1.617$ ,  $N_Z = 1.636$ ,  $N_Z - N_X = 0.022$ . Colorless, white, pale blue or green, gray, brown.

**INCL.** Greenockite (CdS) has been found as fine particles along surfaces of growth of hemimorphite.

**OCCUR.** Hemimorphite is found in veins with smithsonite and sphalerite; also disseminated in limestone with sulfides.

**DIAG.** Strong dispersion, mode of occurrence, and crystal forms are distinctive.

**Lawsonite**  $[\text{CaAl}_2(\text{OH})_2\text{Si}_2\text{O}_7 \cdot \text{H}_2\text{O}]$  is orthorhombic dipyramidal<sup>54</sup> with  $a:b:c = 0.664:1:1.495$ . Space group  $Cmcm$ ;  $a$  5.87,  $b$  8.85,  $c$  13.22 Å. U.C. 4. Crystals prismatic, basal plates, or varied, with perfect 010 and 001 and poor 110 cleavages. Twinning on 110.  $H. = 8$ .  $G. = 3.1$ .  $F. = 4$ . Insoluble in acid. Gelatinizes in acid after fusion.  $Y = b$ ;  $Z = c$ . See Fig. 376.  $(+)2V = 84^\circ$ ,  $r > v$  strong.  $N_X = 1.665$ ,  $N_Y = 1.674$ ,  $N_Z = 1.684$ ,  $N_Z - N_X = 0.019$ . Colorless to bluish; colorless in thin section, but in thick plates  $X = \text{blue}$ ,  $Y = \text{yellowish}$ ,  $Z = \text{colorless}$ . Found in schists and also in saussuritized gabbro, as in the Alps, the Apennines, on Corsica, or near Berkeley, California. Lawsonite has higher relief than most secondary minerals; it differs from zoisite and andalusite by its stronger birefringence, and from scapolite by its biaxial character.

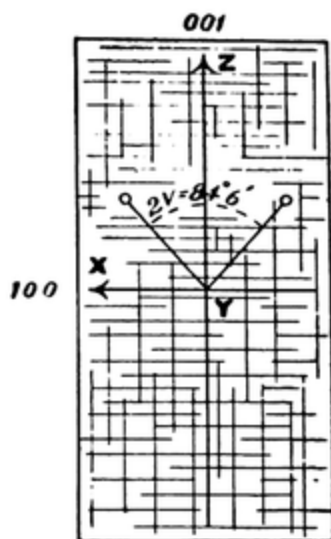


FIG. 376. The optic orientation of lawsonite.

**Clinohedrite**<sup>55</sup>  $[\text{Ca}_2\text{Zn}_2(\text{OH})_2\text{Si}_2\text{O}_7 \cdot \text{H}_2\text{O}]$  is monoclinic domatic with  $a:b:c = 0.682:1:0.323$ ,  $\beta = 103^\circ 56'$ . Crystals varied, clinohedral, with perfect 010 cleavage.  $H. = 5.5$ .  $G. = 3.33$ .  $F. = 4$  with exfoliation. Gelatinizes with HCl.  $Y \wedge c = +28^\circ$ ;

$Z = b$ .  $(-)2V = \text{large}$ ,  $N_X = 1.662$ ,  $N_Y = 1.667$ ,  $N_Z = 1.669$ ,  $N_Z - N_X = 0.007$ . Colorless to white or amethystine. Found with garnet, willemite, etc., at Franklin, New Jersey.

## 2. Type formula $A_m(\text{B}_5\text{X}_{16})_n$

**Zunyite**  $[\text{Al}_{13}\text{O}_4(\text{OH}, \text{F}, \text{Cl})_{19}\text{Si}_5\text{O}_{16}]$  is isometric hextetrahedral; space group<sup>56</sup>  $F\bar{4}3m$ ;  $a$  13.82 Å. U.C. 4. Crystals tetrahedral with poor 111 cleavage.  $H. = 7$ .  $G. = 2.87$ .  $F. = 7$ , but becomes opaque. Insoluble. Isotropic with  $N = 1.589$  (Larsen<sup>34</sup>); 1.602 (Albis<sup>57</sup>);  $F - C = 0.0094$ . Also weakly birefringent<sup>58</sup> (0.002). Colorless. Found in altered porphyry, as at Red Mountain, Colorado.

<sup>53</sup> Uniaxial at  $\lambda = 327 \text{ m}\mu$  and the optic plane is 010 in the ultraviolet—P. Sève: *Jour. Phys. Rad.*, V, 249 (1924); *Min. Abst.*, III, 98 (1926).

<sup>54</sup> B. Gossner and F. Mussnug: *Cent. Min.*, 1931A, 419. Lawsonite and ilvaite are related crystallographically—see H. Strunz: *Zeit. Krist.*, XCVI, 504 (1937). See also F. E. Wickman: *Ark. Kemi, Min. Geol.*, XXVA, No. 2 (1947), who gives the space group  $C222_1$ , and interchanges  $a$  and  $b$ .

<sup>55</sup> C. Palache: *U. S. Geol. Surv. Prof. Paper* 180 (1935).

<sup>56</sup> L. Pauling: *Zeit. Krist.*, LXXXIV, 442 (1933).

<sup>57</sup> M. Albis: *Min. Abst.*, II, 43 (1923).

<sup>58</sup> K. I. Astashenko and V. A. Moleva: *Min. Abst.*, VII, 462 (1940).

## F. NESOSILICATES (SINGLES)

1. Type formula  $A_m(BX_4)_n$ 

Nesosilicates have  $SiO_4$  (or a multiple) in their formulas because the  $SiO_4$  groups have no oxygen atoms in common. Nesosilicates are numerous and range from simple to complex in composition.

## (a) WITHOUT ADDITIONAL ANIONS—ANHYDROUS

## GARNET GROUP

The garnet group consists of rather complex silicates<sup>1</sup> whose formulas may be summarized as  $A_3B_2(SiO_4)_3$  in which A may be Ca, Mg, Fe'', or Mn'' and B may be Al, Fe''', or Cr. Ti may be present in limited amount and also Mn'''. Finally,  $SiO_4$  may be replaced by<sup>2</sup>  $PO_4$  to about 4%  $P_2O_5$ , or by<sup>3</sup>  $2H_2O$  as in *hübischite* and artificial  $3CaO \cdot Al_2O_3 \cdot 6H_2O$ . The chief types of garnet are:

Species	Subspecies		$a(\text{\AA})$
Pyrospite	Pyrope	$Mg_3Al_2Si_3O_{12}$	11.44 <sup>4</sup>
	Almandite	$Fe_3Al_2Si_3O_{12}$	11.49
	Spessartite	$Mn_3Al_2Si_3O_{12}$	11.59
Ugrandite <sup>5</sup>	Uvarovite	$Ca_3Cr_2Si_3O_{12}$	12.05
	Grossularite	$Ca_3Al_2Si_3O_{12}$	11.84
	Andradite	$Ca_3Fe_2Si_3O_{12}$	12.04

In India garnets containing up to 10%  $Mn_2O_3$  have been found. Natural garnets only rarely approach any single formula, but are crystal solutions of two or more end-members. Ford<sup>6</sup> found that one-sixth of all analyzed garnets could be represented by only two formulas (no others greater than 5 per cent); another sixth required four or more formulas (each at least 5 per cent); and the remaining two-thirds required three formulas. In garnet whose composition is expressed by three (or four) formulas, two (or even one) are always predominant and the third (also the fourth) averages about 5 per cent and is not known to exceed 20 per cent. The approximate mutual solubilities of the two

<sup>1</sup> A. R. Alderman (*Mineral. Mag.*, XXIV, 42, 1935) argues cogently that Fe'''Al can proxy, in part, for ASi in garnet. The writer would prefer the view that AlAl can proxy for ASi—just as in pyroxene, amphibole, and mica.

<sup>2</sup> B. Mason and T. Berggren: *Geol. För. Förh. Stockholm*, LXIII, 413 (1942).

<sup>3</sup> C. O. Hutton: *Trans. Roy. Soc. New Zealand*, LXXIII, 174 (1943).

<sup>4</sup> M. Fleischer: *Am. Mineral.*, XXII, 751 (1937).

<sup>5</sup> *Grandite* is a simple designation for the grossularite-andradite series.

<sup>6</sup> W. E. Ford: *Am. Jour. Sci.*, CXC, 33 (1915)

kinds of garnet and the continuity of the grossularite-andradite series are shown in Fig. 377, as determined by Boeke<sup>7</sup> from a study of all analyses. These limits are subject to correction, but it is reasonable to

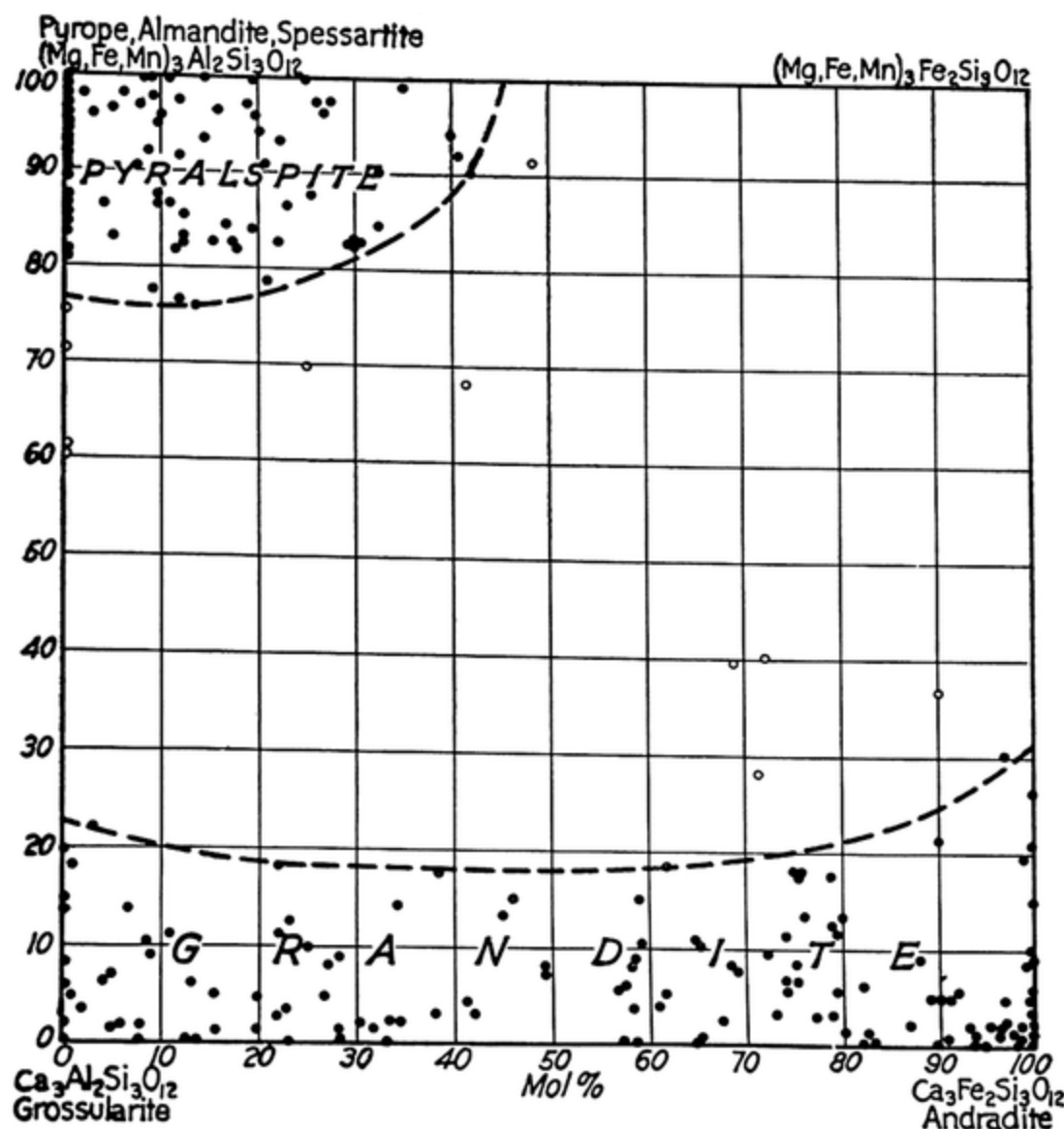


FIG. 377. Variations in composition of garnet. Each dot represents an analysis. Modified from Boeke: *Zeit. Krist.*, LIII, 149 (1914).

think that there is no continuous variation from ugrandite to pyrospite, although Fermor<sup>8</sup> has described a garnet intermediate between spessartite and andradite, and there is no doubt that Ca can be replaced by Mn more easily than by Fe or Mg.

The differences in specific gravity and refractive index between the two kinds of garnet (and their intermediate varieties) are shown in Fig. 378; furthermore pyrospite is practically always isotropic, whereas

<sup>7</sup> H. E. Boeke: *Zeit. Krist.*, LIII, 149 (1914).

<sup>8</sup> L. L. Fermor: *Mem. Geol. Surv. India*, XXXVII (1909).



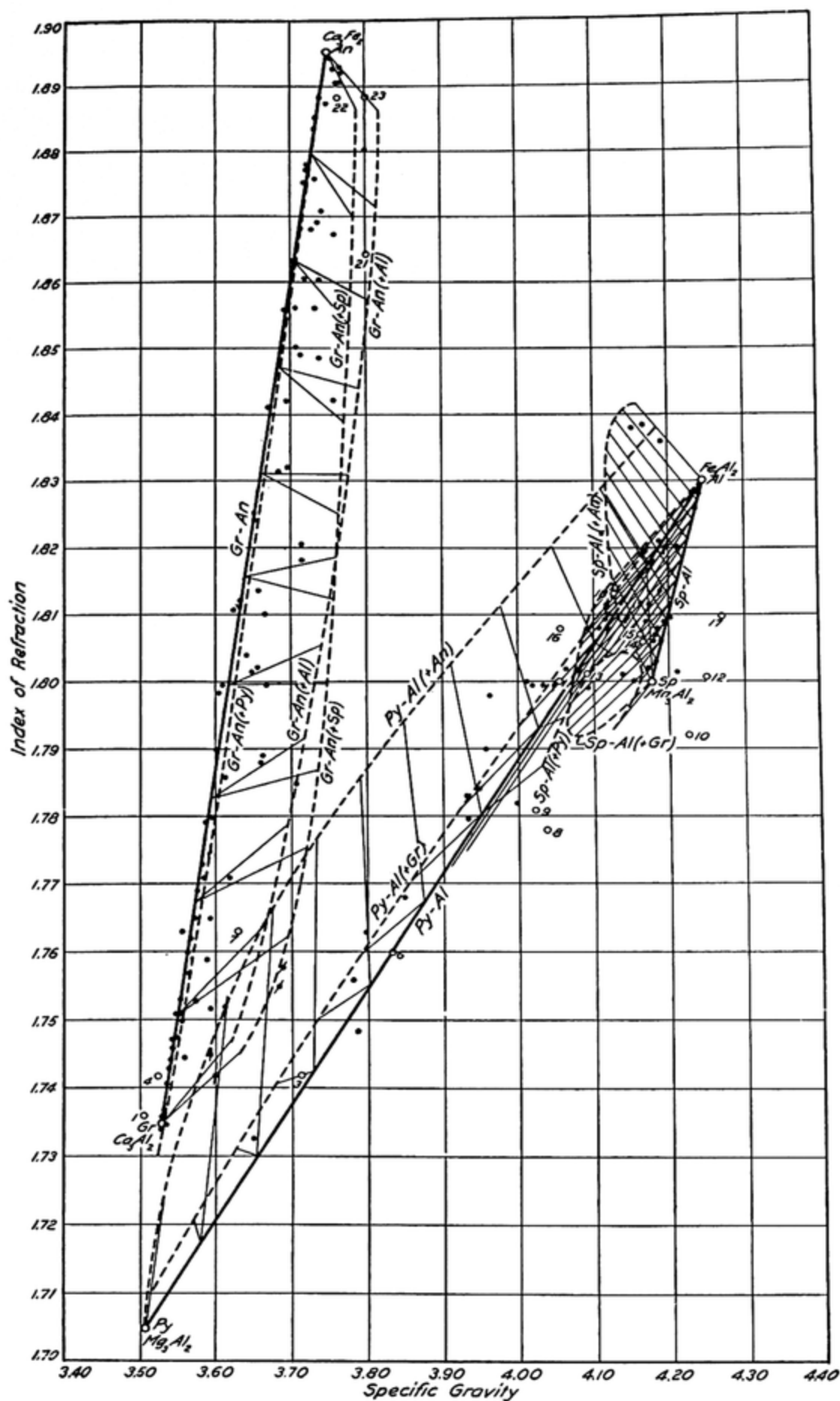


FIG. 378. Properties of garnets.

ugrandite is commonly anisotropic. The specific gravity, refractive index, colors, and pyrognostic characters of the main varieties of garnet are summarized in the following table.

Species	Subspecies	G.	N	Colors	Pyrognostic characters
Pyralspite	Pyrope	3.51	1.705	Red to nearly black	F. = 4 to black non-magnetic globule
	Almandite	4.32	1.83	Brown, red, black	F. = 3 to dark magnetic globule
	Spessartite	4.18	1.80	Shades of red	F. = 3 to black non-magnetic globule. Reacts for Mn.
Ugrandite	Uvarovite	3.78	1.86	Emerald green	F. = 7. Reacts for Cr.
	Grossularite	3.53	1.735	Yellow, white, brown, red, green	F. = 3 to pale non-magnetic globule
	Andradite	3.83	1.895	Yellow, brown, red, black	F. = 3 to black magnetic globule

## PYRALSPITE

<b>Pyrope</b>	ISOMETRIC HEXOCTAHEDRAL	$\text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12}$
<b>Almandite</b>	ISOMETRIC HEXOCTAHEDRAL	$\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$
<b>Spessartite</b>	ISOMETRIC HEXOCTAHEDRAL	$\text{Mn}_3\text{Al}_2\text{Si}_3\text{O}_{12}$

COMP. Pyralspite may contain up to about 25 per cent of grossularite (or andradite) as shown in Figs. 377, 378, 383, and 384. There is a continuous series from pyrope to almandite (but not to spessartite) and also from almandite to spessartite.

STRUC. Space group  $Ia3d$ ;  $a$  11.43 (pyrope) to 11.58 Å (spessartite). U.C. 8.

PHYS. CHAR. Crystal form rare in pyrope; usually the dodecahedron or trapezohedron {211} in almandite and spessartite. See Figs. 379-381. Faces may be striated in almandite in which indistinct 110 parting is known. No cleavage. H. = 7-7.5. G. = 3.5-3.8 (pyrope), 4.1-4.3 (almandite), 3.8-4.25 (spessartite). F. = 3-4 to dark globule, magnetic if Fe is present. Insoluble even in HF.

OPT. PROP. Isotropic; but spessartite may be indistinctly anisotropic. N = 1.70-1.83 varying with the composition as shown in Figs. 382-384 and the following table:

	MgO	FeO	Fe <sub>2</sub> O <sub>3</sub>	MnO	N	G.
Pyrope (calc.)	29.8				1.705	3.51
"Rhodolite"	17.2	15.6	1.9		1.76	
Almandite (calc.) {		43.3			1.83	4.32
	1.0	27.8		14.3	1.818	
Spessartite (calc.)				43.0	1.80	4.18

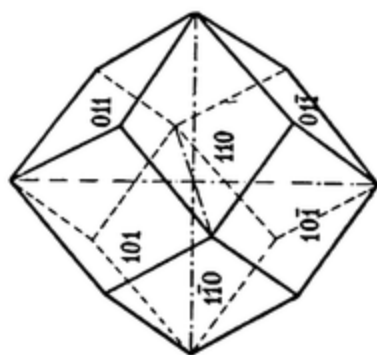


Fig. 379. A crystal form of garnet.



Fig. 380. Garnet in heavy residues from sediments. Photomicrograph by Mrs. F. C. Edson.

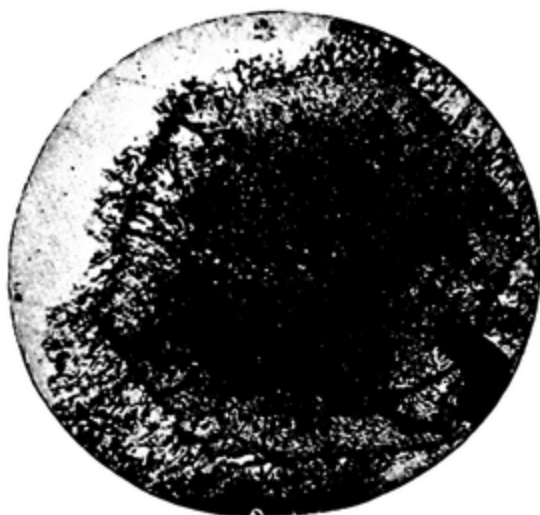


Fig. 381. Photomicrograph of a large garnet crystal in thin section.

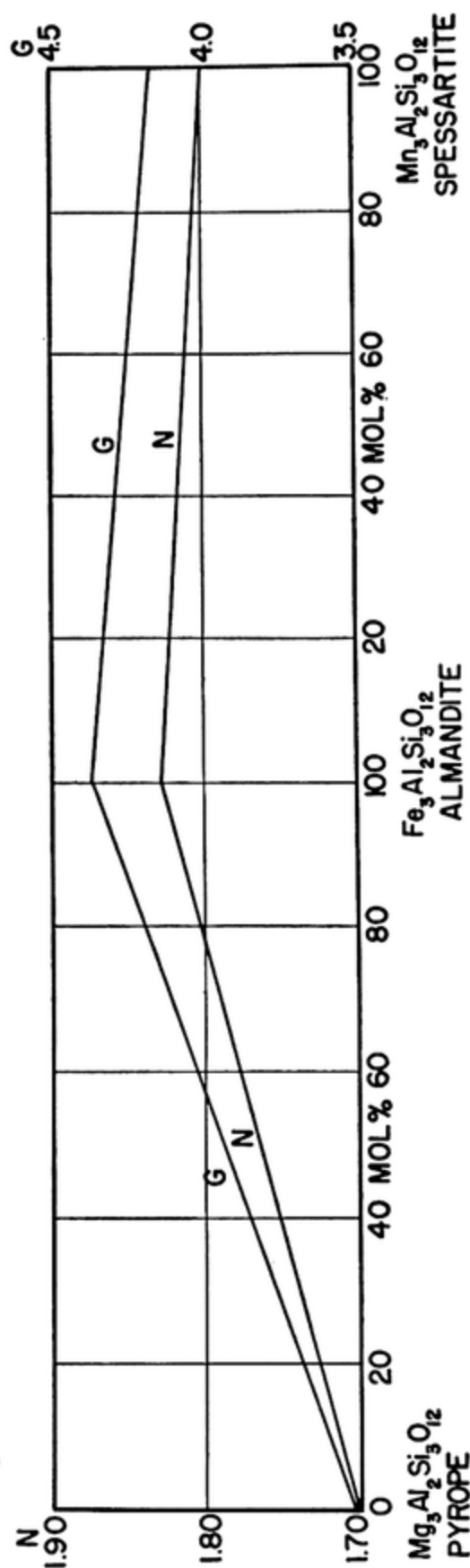


Fig. 382. Properties of the pyrospite double series.

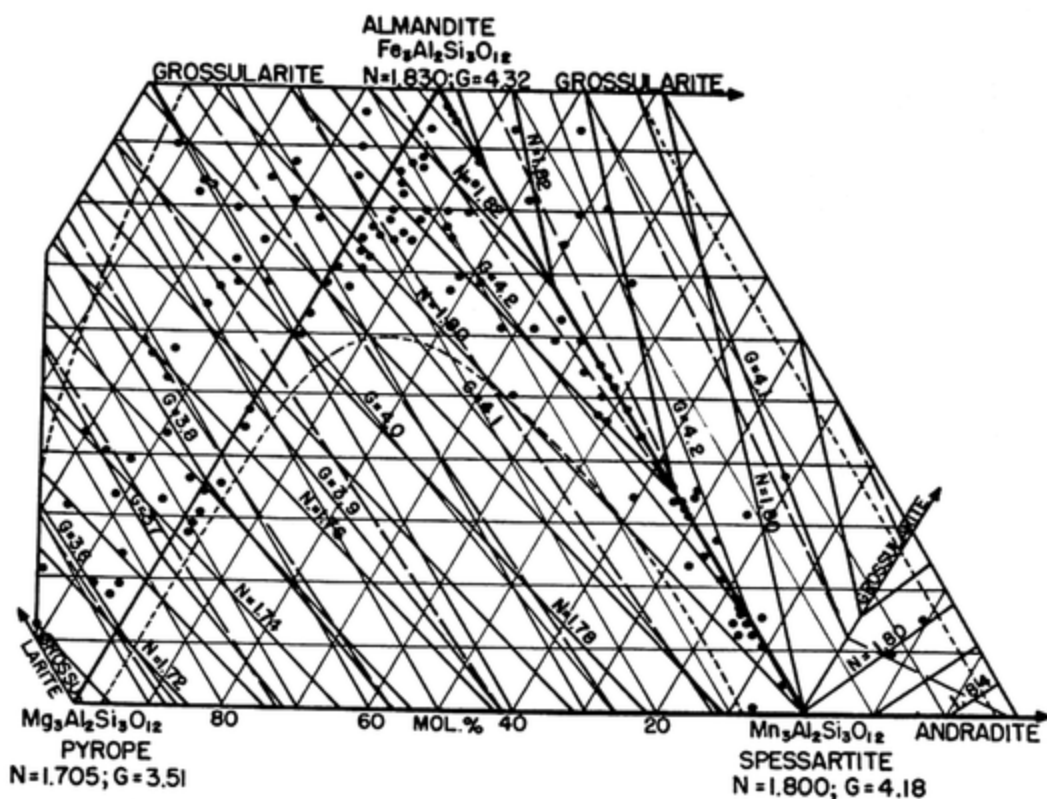


FIG. 383. Properties of the pyralspite system (with some grossularite). Each dot represents an analysis. Dotted lines indicate estimated limits of mutual solubilities.

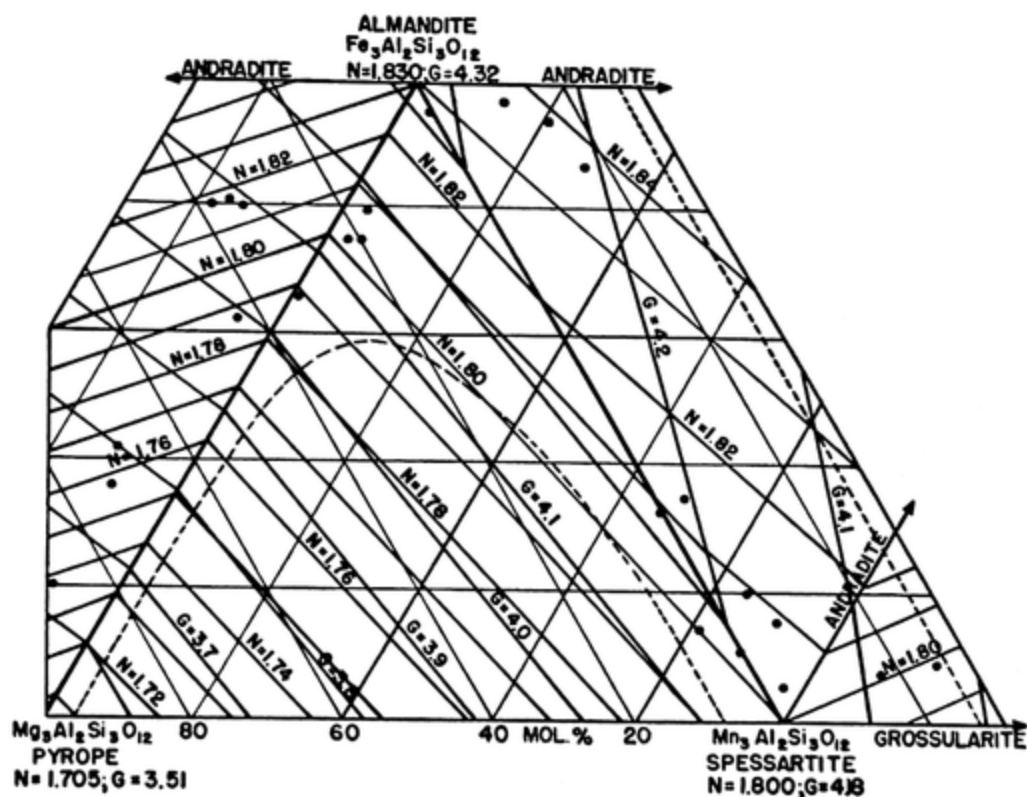


FIG. 384. Properties of the pyralspite system (with some andradite). Each dot represents an analysis. Dash lines represent estimated limits of mutual solubilities.

Color of pyrope red of various shades, rarely black; in thin section red to yellowish brown. Color of almandite red, brownish, violet, black; in thin section brown to reddish. Color of spessartite red of various shades to yellowish brown; in thin section pale pink.

**ALTER.** Pyrope alters to a green substance, called *kelyphite*, which forms a crust about the garnet grains; it is usually an intergrowth of fibrous amphibole and feldspar. Pyrope also alters to chlorite. Almandite alters readily to chlorite and epidote; less commonly to biotite, hornblende, scapolite, feldspar, hematite, etc. When fused and recrystallized in nature it may form a green spinel and hypersthene. Spessartite may alter to biotite.

**OCCUR.** Pyrope is found especially in peridotites and derived serpentines; it is found in the "blue ground" of diamond mines of South Africa. Almandite is common in schists, gneisses, and some granulites; it is an important constituent of eclogite and found in some amphibolites; it is rare in granite and contact rocks. Spessartite is found in mica schist, pegmatite, quartzite, and in lithophysae in rhyolite.

**DIAG.** Pyralspite differs from ugrandite in the almost complete absence of birefringence, which is common in ugrandite; this fact together with a determination of the refractive index and the use of Figs. 378 and 382-384 will give the approximate composition of the garnet. Further, pyrope seems to be confined to peridotites and serpentine.

## UGRANDITE

<b>Uvarovite</b>	ISOMETRIC HEXOCTAHEDRAL	$Ca_3Cr_2Si_3O_{12}$
<b>Grossularite</b>	ISOMETRIC HEXOCTAHEDRAL	$Ca_3Al_2Si_3O_{12}$
<b>Andradite</b>	ISOMETRIC HEXOCTAHEDRAL	$Ca_3Fe_2Si_3O_{12}$
(above 800°)		

**COMP.** Ugrandite may contain up to about 20 per cent of pyralspite in crystal solution, as shown in Fig. 377. It contains up to about 20%  $TiO_2$  in the variety *schorlomite*, and up to 15%  $H_2O$  in the variety *hibschite*. There is a continuous series from grossularite to andradite and probably to uvarovite.

**STRUC.** Space group  $Ia3d$ ;  $a$  11.84 (grossularite) to 12.04 Å (andradite). U.C. 8.

**PHYS. CHAR.** Crystals usually dodecahedral {110}; the trapezohedron {211} alone or with {110} is not rare; small hexoctahedral faces of {321} may be present. Striations may occur on dodecahedral faces. No cleavage. Sometimes a distinct parting on {110}.  $H. = 6.5-7$ .  $G. = 3.4-3.8$  (uvarovite), 3.4-3.6 (grossularite), 3.7-4.1 (andradite).  $F. = 7$  (uvarovite), 3 to pale non-magnetic globule (grossularite). 3.5

to black magnetic globule (andradite). Nearly or quite insoluble even in HF. But *schorlomite* gelatinizes with HCl.

OPT. PROP. Small crystals may be isotropic, but ugrandite usually shows weak birefringence, especially in thick sections. The isometric external form is then retained by twinning, the units being pyramids whose vertices meet at the center and whose bases form the external faces of the isometric form. Some garnets can be separated mechanically into parts which are these twin units.

The various types of twinning correspond with the external form as follows:

1. Dodecahedral type (the commonest). The crystal is composed of twelve rhombic pyramids in each of which the optic plane is parallel to the long diagonal of the rhombic face and the obtuse bisectrix X is normal to that face. The optic angle ( $2V$ ) is about  $50^{\circ}$ – $90^{\circ}$ , and the dispersion is strong with  $r < v$ . The birefringence<sup>9</sup> may attain 0.003.

2. Hexoctahedral type. The crystal contains forty-eight unsymmetrical triangular pyramids; in each the optic plane makes an angle of  $2^{\circ}$ – $17^{\circ}$  with the long diagonal of the dodecahedral face, while the negative acute bisectrix X is somewhat inclined to a normal to that face.

3. Trapezohedral type. The crystal contains twenty-four pyramids in each of which the optic plane is normal to the symmetrical diagonal of the trapezohedral face to which the positive acute bisectrix is also perpendicular.

4. Octahedral type. Rare octahedral garnets from Elba are composed of eight triangular pyramids each of which is uniaxial, the negative optic axis being normal to the octahedral face.

5. In some garnets more than one type of twinning may be present in a single crystal. Also, the crystal may be built up of zones or layers which may be separated mechanically; one zone may show one type of twinning and the next zone a different one. In some crystals different types interpenetrate. Finally, crystals are often composed of parts which are anisotropic and other parts which are isotropic.

Ugrandite has high refringence with  $N = 1.735$  to  $1.895$ ; the variations of index with variations in composition are shown in Figs. 378, 385–387 and in the following table:

	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	Cr <sub>2</sub> O <sub>3</sub>	N	G.
Grossularite (calc.)	22.7				1.735	3.53
Grossularite <sup>10</sup>	19.61	3.73	1.71		1.748	3.62
Andradite <sup>11</sup>	5.69	24.94	3.07		1.88	3.76
Andradite (calc.)		31.5			1.895	3.83
Uvarovite <sup>12</sup>	1.13	2.46		27.04	1.84	3.75
Uvarovite (calc.)				30.6	1.86	3.78

<sup>9</sup> J. H. Taylor: *Am. Mineral.*, XX, 120 (1935), describes a garnet with sectoral twinning and  $(+)2V = 75^{\circ}$ – $90^{\circ}$ ,  $r > v$  strong,  $N_Y$  varying from 1.756 to 1.784, and  $N_Z - N_X =$  about 0.012!

<sup>10</sup> W. M. Agar and P. Krieger: *Am. Jour. Sci.*, XXIV, 68 (1932).

<sup>11</sup> W. Kunitz: *N. Jahrb. Min.*, Bl. Bd. LXXA, 395 (1935).

<sup>12</sup> P. Eskola: *Min. Abst.*, VI, 46 (1935).



Color of uvarovite emerald green; in thin section green. Color of grossularite yellow, brown, gray, greenish, white, red, and colorless to yellowish brown in thin section. Color of andradite black to red, brown, greenish yellow; often dark-colored even in thin section. Not pleochroic.

**INVER.** The birefringent type inverts<sup>13</sup> at about 800° to a truly isotropic condition. Ugrandite of igneous rocks does not always invert to the birefringent state on cooling.

**ALTER.** Uvarovite may alter to dark green chlorite, doubtless containing chromium. Grossularite is known to alter to epidote, chlorite, feldspar, and calcite. Andradite may change to epidote, limonite, feldspar, and calcite.

**OCCUR.** Uvarovite is rare, but is known in gneiss, serpentine, and in cavities in chromite, as well as in contact-altered limestones, as at Kyshtym in the Urals, and in the Pyrenees. Grossularite is common in limestone contact zones, and is also found in schists, in veins, and in nepheline syenite. Andradite is not rare in limestone contacts and is found also in schists, serpentine, nepheline syenite, and some acid igneous rocks.

**DIAG.** Ugrandite usually shows birefringence, which is rare in pyralisite; this difference together with a measurement of the refractive index and the use of the table on page 486 and the graphs of Figs. 378 and 385-387 will give the approximate composition of the garnet.

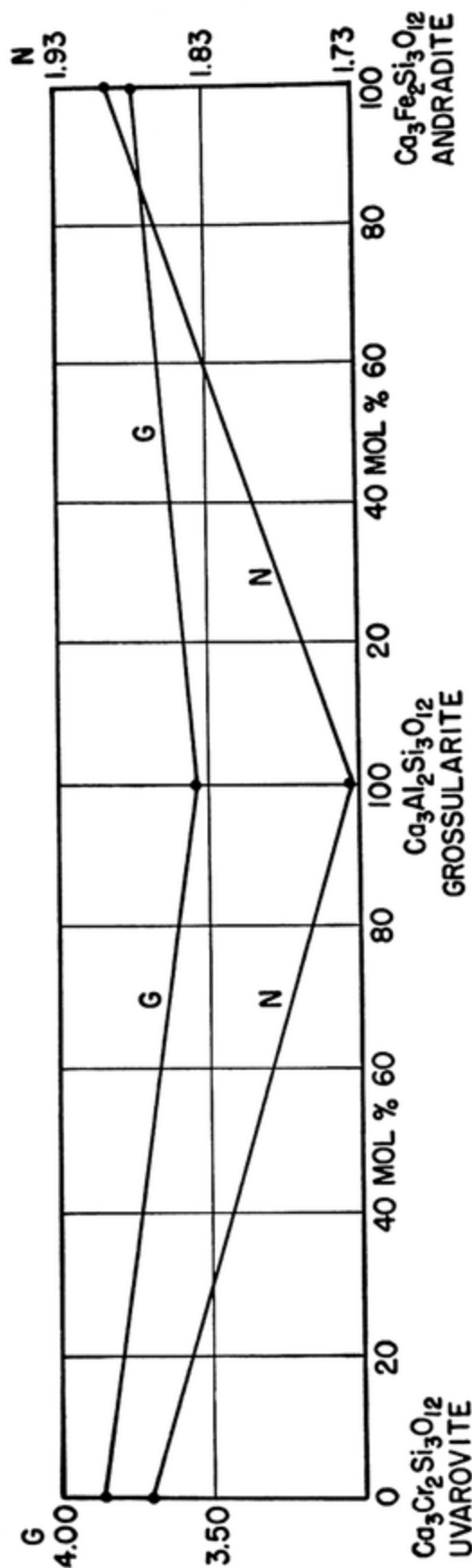


FIG. 385. Properties of the ugrandite double series.

<sup>13</sup> H. E. Merwin in C. W. Wright: *U. S. Geol. Surv. Prof. Paper* 87, 108 (1915).

Further, ugrandite is common in limestone contacts, where pyralspite is rare.

*Schorlomite* is a titaniferous ugrandite (usually andradite); increase of  $\text{TiO}_2$  causes increase of refringence, but the relation is not simple since other elements also vary.

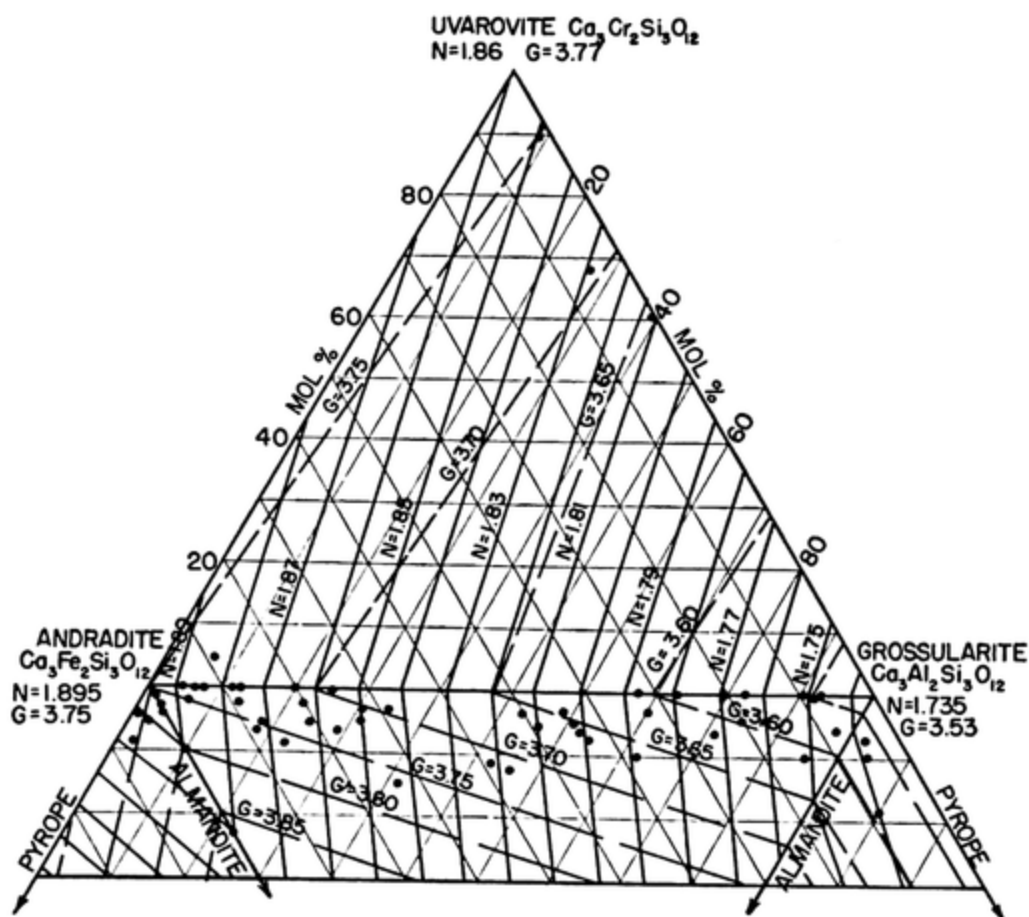


FIG. 386. Properties of the ugrandite system (with some almandite). Each dot represents an analysis.

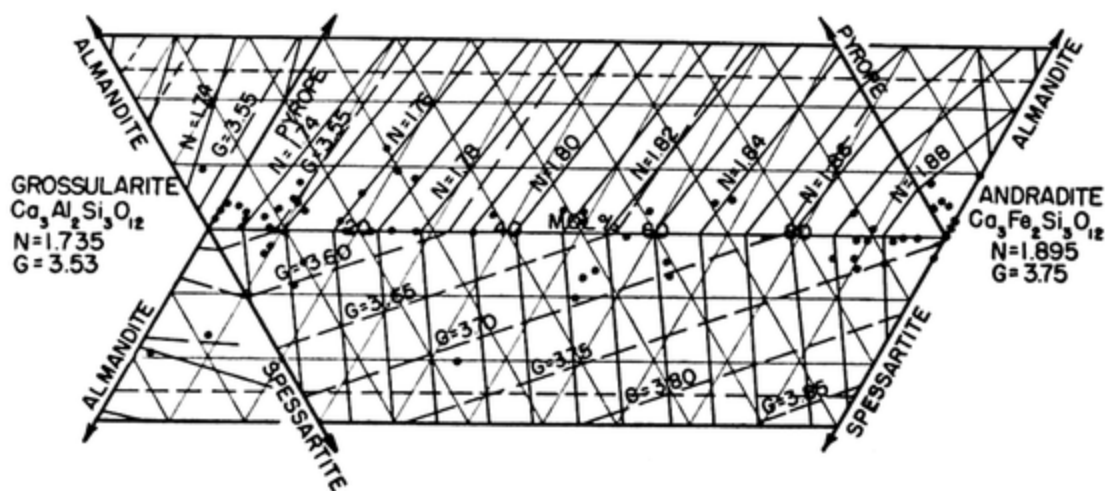


FIG. 387. Properties of the grandite series (with some pyralspite).

Schorlomite is grayish black, hence the name for black garnet (*melanite*) is sometimes applied to it. The following data<sup>14</sup> illustrate variations in index.

	TiO <sub>2</sub>	N
Melanite, New Haven, Connecticut	0.0	1.86–1.88
Schorlomite <sup>15</sup> ("Andradite"), Colorado	5.08	1.907
Schorlomite ("Melanite"), Colorado	5.1	1.95
Schorlomite <sup>16</sup> ("Melanite"), Italy	8.7	1.94
Schorlomite, Magnet Cove, Arkansas	16.9	1.94
Schorlomite, Magnet Cove, Arkansas	?	1.98
Schorlomite ("Ivaarite"), Finland	19.0	2.01

Schorlomite is found sometimes in syenite or phonolite.

**Hibschite**<sup>17</sup> ( $3CaO \cdot Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$ ) is a mineral belonging to the series (known artificially) between  $Ca_3Al_2Si_3O_{12}$  and  $Ca_3Al_2(OH)_{12}$ . See Fig. 388. Crystals dodecahedral without cleavage. H. = 6.5. G. = 3.13. Isotropic with N = 1.67–1.68; also may be weakly birefringent. With no silica (not yet found in nature)

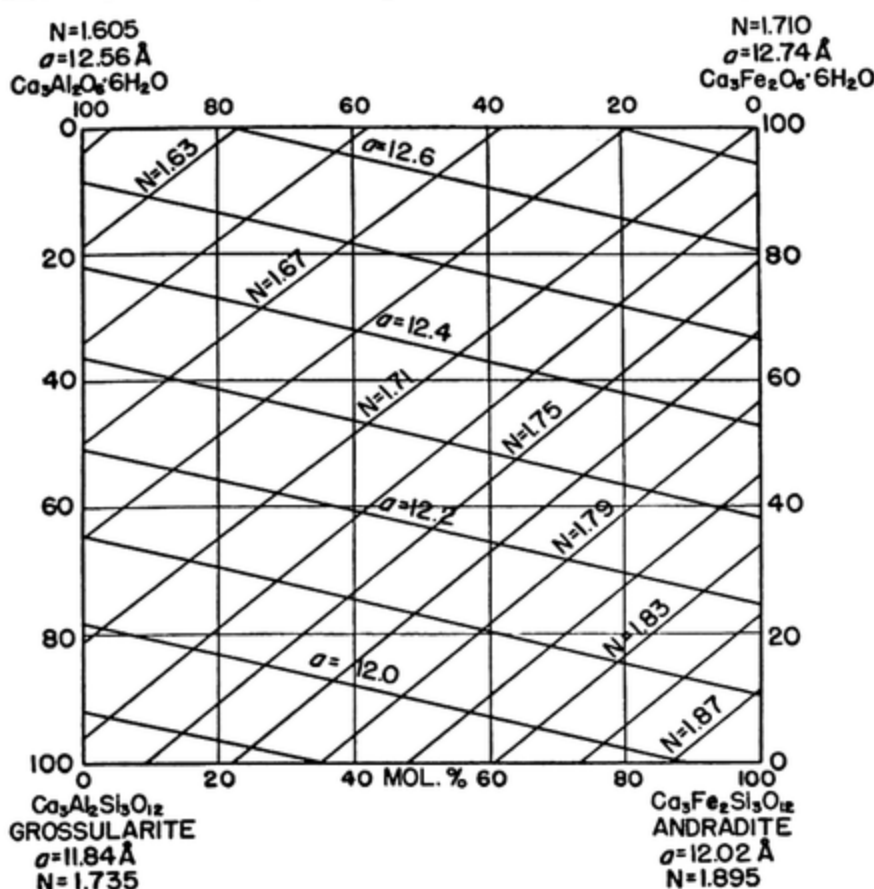


FIG. 388. Properties of the grandite- $Ca_3(Al,Fe)_2O_6 \cdot 6H_2O$  system.

<sup>14</sup> H. S. Washington: *Am. Jour. Sci.*, CC, 33 (1920).

<sup>15</sup> E. S. Larsen and J. F. Hunter: *J. Wash. Acad. Sci.*, IV, 478 (1914).

<sup>16</sup> Further,  $SiO_2 = 29.7$ ,  $Al_2O_3 = 8.1$ ,  $Fe_2O_3 = 23.6$ ,  $MgO = 0.7$ ,  $CaO = 28.8$ .

<sup>17</sup> Also called *plazolite*, *hydrogarnet*, *hydrogrossular*, *grossularoid*, and *garnetoid*—see M. Fleischer: *Am. Mineral.*, XXIX, 247 (1944). Included here in spite of being hydrous because of structural similarity to garnet.

it has  $G. = 2.52$ ,  $N = 1.60$ . Colorless. Found in contact-altered limestone, as at Marienberg, Bohemia.

**Eulytite** ( $\text{Bi}_4\text{Si}_3\text{O}_{12}$ ) is isometric hextetrahedral; <sup>18</sup> space group <sup>18</sup>  $I\bar{4}3d$ ;  $a$  10.27 Å. U.C. 4. Crystals minute tetrahedrons with poor 110 cleavage.  $H. = 4.5$ .  $G. = 6.6$ .  $F. = 2$ . Gelatinizes with HCl. Isotropic with  $N = 2.05$ ; also weakly birefringent and uniaxial,<sup>19</sup> or biaxial<sup>20</sup> with  $(+)2V = 80^\circ$  and  $N_z - N_x = 0.0015$ . Color brown, yellow, gray. Found with bismuth in Saxony.

**ZIRCON** DITETRAGONAL DIPYRAMIDAL <sup>21</sup>  $c/a = 0.891$   $\text{ZrSiO}_4$

**COMP.** Zircon may contain some  $\text{Fe}_2\text{O}_3$ ,  $\text{ThO}_2$ ,  $\text{Y}_2\text{O}_3$ ,  $\text{HfO}_2$ ,  $\text{U}_2\text{O}_3$ ,  $\text{H}_2\text{O}$ , etc.

**STRUC.** Space group <sup>21</sup>  $I4/amd$ ;  $a$  6.60,  $c$  5.88 Å. U.C. 4.

**PHYS. CHAR.** Commonly in square prisms, moderately elongated and terminated by pyramid faces. Twinning on 111 uncommon. See

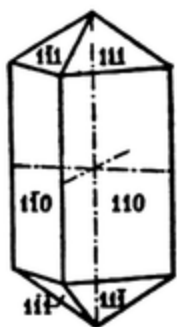


FIG. 389. A crystal habit of zircon.

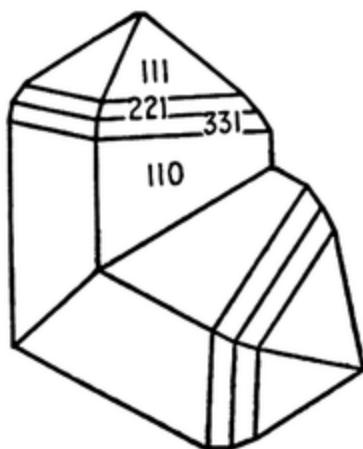


FIG. 390. A geniculated twin of zircon.

Figs. 389 and 390. Poor prismatic cleavage.  $G. = 4.66$ – $4.7$ .  $H. = 7.5$ .  $F. = 7$ . Slowly attacked by concentrated  $\text{H}_2\text{SO}_4$ .

**OPT. PROP.** Uniaxial positive with high refringence and very strong to extreme birefringence. Optic properties vary with variations in original composition and also with variations of crystallinity—the original crystal gradually alters to an amorphous state (called *metamict*) apparently due to effects of radioactivity of U and Th in it. As this alteration progresses the  $\text{ZrSiO}_4$  changes to amorphous  $\text{SiO}_2$  and iso-

<sup>18</sup> G. Menzer: *Zeit. Krist.*, LXXVIII, 136 (1931).

<sup>19</sup> C. Frondel: *Am. Mineral.*, XXVIII, 536 (1943).

<sup>20</sup> G. Menzer: *Zeit. Krist.*, CVI, 34 (1945).

<sup>21</sup> R. W. G. Wyckoff and S. B. Hendricks: *Zeit. Krist.*, LXVI, 73 (1927). 110 of the old usage becomes 100.

metric or amorphous  $ZrO_2$ , and the density, refringence, and birefringence decrease, as illustrated in the following approximations:

	Normal Zircon	Partly Altered Zircon ( <i>hyacinth</i> )	Much Altered Zircon ( <i>malacon</i> )
$N_O = 1.92-1.96$		1.90-1.92	1.76-1.90
$N_E = 1.96-2.02$		1.92-1.96	1.76-1.92
$N_E - N_O = 0.04-0.06$		0.02-0.04	0.00-0.02
$G. = 4.6-4.71$		4.2-4.6	3.9-4.2
$H. = 7.5$		7 <i>ca.</i>	6-7

Color yellow, brown, gray, rarely green or colorless. In thin section colorless to pale brown or gray. Pleochroism invisible in thin section, very weak in sections more than 1 mm. thick with  $O < E$ .

Optical anomalies unknown in microscopic crystals, but may be present in large crystals, often with zonal structure. Zircon is then biaxial with small optic angle; for example, olive green *beccarite* from Ceylon has  $(+ )2V = 10^\circ$ ,  $N_X = 1.9272$ ,  $N_Y = 1.9277$ ,  $N_Z = 1.982$ ,  $N_Z - N_X = 0.0548$ , and  $Z = c$ . Such conditions may be due to alteration, being found especially in partly metamict crystals.

**ALTER.** The alteration already described is accompanied by hydration and malacon contains 3 to 10%  $H_2O$ .

**OCCUR.** Zircon is very widely distributed as an accessory constituent of all kinds of igneous rocks, but it is especially common in syenite, granite, and diorite. It seems to be more abundant in plutonic than in volcanic rocks. It is also found in many kinds of metamorphic rocks; it is remarkably resistant to alteration and to attrition, and therefore it can be traced through more than one cycle of erosion and sedimentation, and is a common accessory of many sediments. In igneous rocks it is one of the earliest minerals to crystallize, and therefore it is found enclosed in many other minerals. When enclosed by biotite, chlorite, cordierite, andalusite, sometimes pyroxenes or amphiboles, it may be surrounded by pleochroic halos.

**DIAG.** Zircon may be distinguished from cassiterite by much weaker birefringence, the associated minerals, and chemical reactions; from xenotime by higher refringence, less perfect prismatic cleavage, greater hardness, and chemical reactions; from thorite by much stronger birefringence, greater hardness, and insolubility in  $HCl$ .

**Naegite** is probably related to zircon but contains  $ThO_2$ ,  $Cb_2O_5$ ,  $Y_2O_3$ , and  $UO_3$  with much  $ZrO_2$  and  $SiO_2$ . Probably tetragonal.  $H. = 7.5$ .  $G. = 4.09$ . Often isotropic<sup>22</sup> (due to alteration?) with  $N = 1.818$  *ca.* Color green or brown. Found in placers in Japan.

<sup>22</sup> E. S. Larsen: *U. S. Geol. Surv. Bull.* 679 (1921) and 848 (1934).

**Thorite** ( $\text{ThSiO}_4$ ) is tetragonal with  $c/a = 0.64$ . Crystals square prisms with pyramidal terminations. Distinct 110 cleavage.  $H. = 4.5-5$ .  $G. = 5.2-5.4$ .  $F. = 7$ . Uniaxial positive with  $N_O = 1.8$ ,  $N_E - N_O = 0.01$ . Commonly isotropic from alteration to metamict state; then it may be hydrated and have  $N = 1.68$  to  $1.72+$ , with  $G. = 4.4$  to  $4.8$ . After ignition  $N = 1.78$  ca. Color orange-yellow, brownish to black. Streak light orange to dark brown. Very rarely found unaltered. Occurs in syenite, etc., as at Esmark, Norway, and Franklin, New Jersey.

**Ferrithorite**<sup>23</sup> is a variety containing up to 13%  $\text{Fe}_2\text{O}_3$ , with 3.5 FeO, 5.6 rare earths, 4.1  $\text{Al}_2\text{O}_3$ , etc.  $G. = 4.96$ . Isotropic because metamict.

**Auerlite**<sup>24</sup> ( $\text{ThO}_2 \cdot \text{SiO}_2 \cdot \frac{1}{2}\text{P}_2\text{O}_5 \cdot 2\text{H}_2\text{O}$ ?) is probably thorite with some  $\text{P}_2\text{O}_5$  replacing  $2\text{SiO}_2$ .  $H. = 2.5-3$ .  $G. = 4.1-4.8$ .  $F. = 7$ . Tetragonal and uniaxial positive with  $N_O = 1.65$ ,  $N_E - N_O = 0.01$ . Color yellow. Found in gneiss in Henderson County, North Carolina.

**Mackintoshite**<sup>24</sup> ( $3\text{ThO}_2 \cdot 3\text{SiO}_2 \cdot \text{UO}_2 \cdot 3\text{H}_2\text{O}$ ?) is probably thorite with some  $\text{UO}_2$ .  $H. = 5.5$ .  $G. = 5.4$ .  $F. = 7$ . Tetragonal, but metamict and isotropic with  $N = 1.77$ . Color black; in section nearly colorless, but cloudy. Found in Llano County, Texas.

**Nicolayite**<sup>24</sup> ( $2\text{PbO} \cdot 3\text{ThO}_2 \cdot 4\text{UO}_2 \cdot 8\text{SiO}_2 \cdot 21\text{H}_2\text{O}$ ?) is similar with  $G. = 4.1$  and isotropic<sup>25</sup> with  $N = 1.617$ . Color yellow. Further alteration produces *pilbarite* which has  $H. = 3$ ,  $G. = 4.6$  ca., isotropic with  $N = 1.74$  ca. Color canary yellow. Found in ore deposits at Wodgina, Western Australia.

**Sarcopite** [ $(\text{Ca}, \text{Na})_3\text{Al}_2\text{Si}_3\text{O}_{12}$ ?] is tetragonal dipyramidal<sup>26</sup> with  $c/a = 1.203$ . Space group<sup>26</sup>  $I4/m(?)$ ;  $a$  12.43,  $c$  15.59 Å. U.C. 6. Formula uncertain;<sup>27</sup> formerly referred to melilite,<sup>28</sup> but X-ray study shows a relation to scapolite.<sup>26</sup> Crystals equant, nearly isometric.  $H. = 6$ .  $G. = 2.92$ . Uniaxial positive with  $N_O = 1.6404$ ,  $N_E = 1.6566$ ,  $N_E - N_O = 0.0162$  (Pauly<sup>29</sup>);  $N_O = 1.6035$ ,  $N_E = 1.6147$ ,  $N_E - N_O = 0.0122$  (Zambonini<sup>27</sup>). Color light red; colorless in thin section. Found in volcanic rock at Vesuvius.

**Phenakite** ( $\text{Be}_2\text{SiO}_4$ ) is rhombohedral<sup>30</sup> with  $c/a = 0.665$ . Space group  $R\bar{3}$ ;  $a$  12.40,  $c$  8.24 Å. Hexagonal U.C. 18. Crystals rhombohedral or prismatic; twinning common on  $10\bar{1}0$ . Distinct  $11\bar{2}0$  cleavage.  $H. = 7.5$ .  $G. = 2.98$ .  $F. = 7$ . Insoluble. Uniaxial positive with  $N_O = 1.654$ ,  $N_E = 1.670$ ,  $N_E - N_O = 0.016$ . Colorless, yellow, rose, brown; may be faintly pleochroic in thick plates with  $O =$  colorless,  $E =$  yellow. Found in pegmatite and some metamorphic rocks, as near Miask, U.S.S.R., and Topaz Butte, Colorado.

<sup>23</sup> A. Lacroix: *Minéral. Madagascar*, III, 310 (1923); I. E. Starik et al.: *Min. Abst.*, VIII, 302 (1943).

<sup>24</sup> These minerals are subsilicates and hydrous, but they are placed here because they are so closely related to thorite.

<sup>25</sup> E. S. Simpson: *Min. Abst.*, IV, 346 (1930).

<sup>26</sup> B. Gossner and F. Mussnug: *Cent. Min.*, 1928A, 129 and 167.

<sup>27</sup> F. Zambonini and V. Caglioti: *Min. Abst.*, V, 95 (1932).

<sup>28</sup> A. N. Winchell: *Am. Jour. Sci.*, CCVIII, 375 (1924). H. Berman: *Am. Mineral.*, XIV, 389 (1929).

<sup>29</sup> A. Pauly: *Cent. Min.*, 1906, 266.

<sup>30</sup> G. Switzer: *Am. Mineral.*, XXIV, 791 (1939).



**Willemite** ( $Zn_2SiO_4$ ) is rhombohedral with  $c/a = 0.670$ . Space group <sup>31</sup>  $R\bar{3}$ ;  $a$  12.49,  $c$  8.26 Å. Hexagonal U.C. 18. Crystals hexagonal prisms with 0001 and  $11\bar{2}0$  cleavages.  $H. = 5.5$ .  $G. = 3.9-4.1$ .  $F. = 1510^\circ$ . Gelatinizes with HCl. Uniaxial positive with  $N_O = 1.691$ ,  $N_E = 1.719$ ,  $N_E - N_O = 0.028$  (Palache <sup>32</sup>);  $N_O = 1.697$ ,  $N_E = 1.719$ ,  $N_E - N_O = 0.022$  (Jaeger <sup>33</sup>). A reddish or gray variety containing Mn is called *troostite*; with <sup>34</sup> 6.80 MnO it has  $N_O = 1.714$ ,  $N_E = 1.732$ ,  $N_E - N_O = 0.018$ . In lead slags willemite may have up to 36 mol. %  $Fe_2SiO_4$  and 7%  $Mg_2SiO_4$ ; then  $N_O = 1.701$ ,  $N_E = 1.726$ ,  $N_E - N_O = 0.025$  (Faber <sup>35</sup>); this variety is pleochroic with O = reddish violet, E = bluish violet. Another phase ( $\beta$ - $Zn_2SiO_4$ ) has <sup>36</sup>  $(- )2V = 49^\circ$ ,  $N = 1.700$ ,  $N_Z - N_X = 0.009$ . A third phase ( $\gamma$ - $Zn_2SiO_4$ ) has  $(- )2V = 40^\circ$ ,  $N_X = 1.685$ ,  $N_Y = 1.700$ ,  $N_Z = 1.703$ ,  $N_Z - N_X = 0.018$ . Willemite in nature is white, yellow, green, red, gray, or brown. Found in zinc deposits as at Altenberg, in Belgium, and at Franklin, New Jersey.

**GRANDIDIERITE** ORTHORHOMBIC  $H_2Na_2(Mg,Fe)_7(Al,Fe''',B)_{15}Si_7Al_7O_{56}?$

**PHYS. CHAR.** Crystal faces unknown; perfect 100 and distinct 010 cleavages.  $H. = 7.5$ .  $G. = 3.0$ .  $F. = 7$ . Insoluble in acids.

**OPT. PROP.** The optic plane is 001;  $X = a$ .  $(- )2V = 30^\circ$ ,  $r < v$  very strong.  $N_X = 1.602$ ,  $N_Y = 1.636$ ,  $N_Z = 1.639$ ,  $N_Z - N_X = 0.037$ . Color greenish blue with extreme pleochroism, and  $X =$  dark bluish green, light greenish blue, <sup>37</sup>  $Y =$  colorless,  $Z =$  dark green, light greenish blue, and  $Y < X < Z$ .

**ALTER.** Grandidierite alters readily to a green fibrous mineral similar to the alteration product (kryptotile) of prismatine.

**OCCUR.** It is found in pegmatite and aplite at Andrahoma, Madagascar.

**DIAG.** The pleochroism gives deep color across the elongation and no color parallel thereto.

**Zebedassite** <sup>38</sup> ( $H_8Mg_5Al_2Si_6O_{24}?$ ) is orthorhombic(?); fibrous.  $H. = 2$ .  $G. = 2.19$ .  $F. = 7$ . Gelatinizes with acid.  $Z = c =$  elongation.  $N_Y = 1.52$  ca.,  $N_Z - N_X =$  strong. Colorless. Found in an altered rock at Zebedassi in Piedmont.

## OLIVINE GROUP

The minerals of the olivine group are silicates of divalent bases crystallizing in the orthorhombic system. There is a continuous series from  $Mg_2SiO_4$  to  $Fe_2SiO_4$  and from  $Fe_2SiO_4$  to  $Mn_2SiO_4$  and perhaps from  $Mg_2SiO_4$  to  $Mn_2SiO_4$ . As in the carbonates there is probably a double

<sup>31</sup> C. Gottfried: *N. Jahrb. Min.*, A, LV, 393 (1927).

<sup>32</sup> C. Palache and H. Berman: *Am. Mineral.*, XII, 185 (1927).

<sup>33</sup> F. Jaeger: *Proc. K. Akad. Wet. Amst.*, XVIII, 896 (1916).

<sup>34</sup> H. Otto: *Tsch. Min. Pet. Mit.*, XLVII, 89 (1936).

<sup>35</sup> W. Faber: *Chem. Erde*, X, 67 (1935).

<sup>36</sup> E. Ingerson, G. W. Morey, and O. F. Tuttle: *Am. Jour. Sci.*, CCXLVI, 31 (1948).

<sup>37</sup> J. E. de Villiers: *Mineral. Mag.*, XXV, 550 (1940).

<sup>38</sup> A. Brusoni: *Min. Abst.*, I, 25 (1920).

salt between each of these three and  $\text{Ca}_2\text{SiO}_4$ , and no series to that compound. The chief types are the following:

Species	Subspecies	Formula	$a:b:c$
Olivine proper	Forsterite	$\text{Mg}_2\text{SiO}_4$	0.467:1:0.587
	Chrysolite, etc.	$(\text{Mg,Fe})_2\text{SiO}_4$	0.466:1:0.586
	Fayalite	$\text{Fe}_2\text{SiO}_4$	0.458:1:0.579
	Knebelite	$(\text{Fe,Mn})_2\text{SiO}_4$	0.467:1:?
	Tephroite	$\text{Mn}_2\text{SiO}_4$	0.462:1:0.591
(Artificial)	Picrotephroite	$(\text{Mn,Mg})_2\text{SiO}_4$	?
	(Artificial)	$\text{Ca}_2\text{SiO}_4$	?
?	(Artificial)	$\text{CaFeSiO}_4$	0.437:1:0.577
	Monticellite	$\text{CaMgSiO}_4$	0.434:1:0.576
	Glaucochroite	$\text{CaMnSiO}_4$	0.441:1:0.581
Larsenite		$\text{PbZnSiO}_4$	0.440:1:0.532

It is probable that  $\text{CaFeSiO}_4$ ,  $\text{CaMgSiO}_4$ , and  $\text{CaMnSiO}_4$  are miscible in crystals in all proportions, like the three types of dolomite.

## OLIVINE

ORTHORHOMBIC DIPYRAMIDAL

$(\text{Mg,Fe,Mn})_2\text{SiO}_4$

$a:b:c$

Forsterite	0.467:1:0.587	$\text{Mg}_2\text{SiO}_4$
Fayalite	0.458:1:0.579	$\text{Fe}_2\text{SiO}_4$
Tephroite	0.462:1:0.591	$\text{Mn}_2\text{SiO}_4$

COMP. Binary series of olivine seem to be much more important in nature than the ternary system. Olivine may contain some  $\text{Fe}'''$ , Zn, Ca, (Al?), etc.

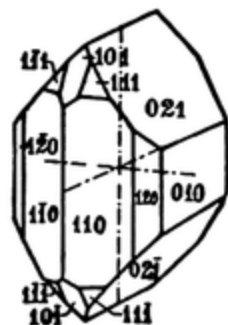


FIG. 391. A crystal habit of olivine.

STRUC. Space group  $Pbnm$ ; for  $^{39} \text{Mg}_9\text{Fe}(\text{SiO}_4)_5$ :  $a$  4.755,  $b$  10.21,  $c$  5.985 Å; for  $^{40} \text{Fe}_2\text{SiO}_4$ :  $a$  4.80,  $b$  10.59,  $c$  6.16 Å. For  $\text{Mn}_2\text{SiO}_4$ :  $a$  4.86,  $b$  10.62,  $c$  6.22 Å. U.C. 4.

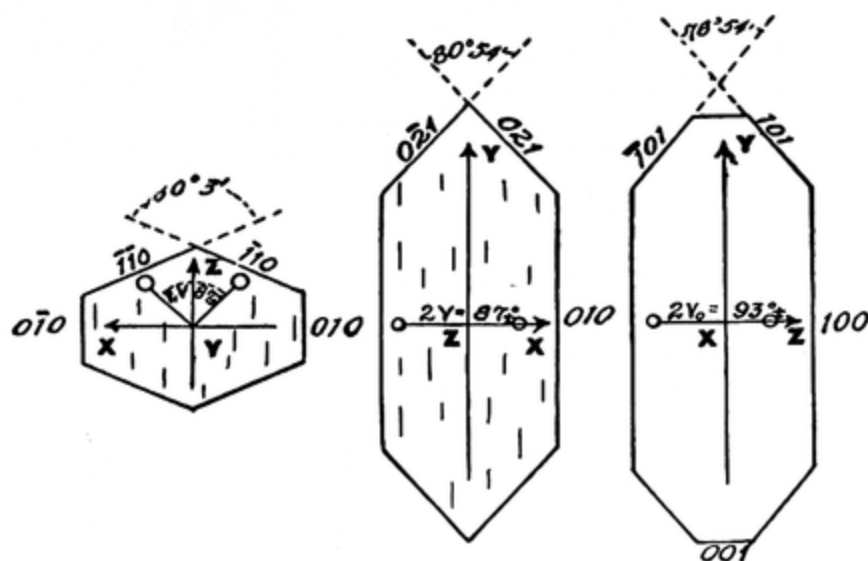
PHYS. CHAR. Crystals usually somewhat elongated parallel to  $c$ ; rarely parallel to  $a$ ; commonly with good development of  $\{110\}$ ,  $\{010\}$ ,  $\{021\}$ ,  $\{100\}$ ,  $\{101\}$ , etc.; see Fig. 391; also granular massive. Twinning rare, on 011, 012, or 031. Distinct  $^{41}$  010 and less distinct 100 cleavages.  $H.$  = 6.5–7.  $G.$  = 3.2 ( $\text{Mg}_2\text{SiO}_4$ ); 3.5 ( $\text{Mn}_2\text{SiO}_4$ ); 4.4 ( $\text{Fe}_2\text{SiO}_4$ ).  $F.$  = 7 ( $1890^\circ$ — $\text{Mg}_2\text{SiO}_4$ ); 4 ( $\text{Fe}_2\text{SiO}_4$ ); 3.5 ( $\text{Mn}_2\text{SiO}_4$ ). Gelatinizes with HCl.

<sup>39</sup> W. L. Bragg and G. B. Brown: *Zeit. Krist.*, LXIII, 538 (1926); see also *Min. Abst.*, IX, 231 (1946).

<sup>40</sup> F. Rinne: *Zeit. Krist.*, LIX, 230; F. Rinne et al.: *Zeit. Krist.*, LIX, 548 (1924).

<sup>41</sup> H. E. Hawkes: *Am. Mineral.*, XXXI, 276 (1946), reports olivine in one occurrence with remarkably well-developed cleavages parallel to 010 and 100. Cleavages are rarely distinct in thin section.

OPT. PROP. The optic plane is 001;  $X = b$ ,  $Z = a$ . See Figs. 392–394.  $Mg_2SiO_4$  is optically positive, but all other parts of the system are



FIGS. 392–394. The optic orientation of olivine ( $2V_X$  varies from  $99^\circ$  to  $47^\circ$ ).

optically negative. Dispersion  $r > v$  weak about  $X$ . Refrindex high and birefringence strong—see Figs. 395 and 396, and the following data:

	Composition	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$	$2V_X$
Forsterite	$Mg_2SiO_4$	1.635	1.651	1.670	0.035	$99^\circ$
Chrysolite	$Fe_{80}Fa_{20}$	1.674	1.692	1.712	0.038	$87^\circ$
Hyalosiderite	$Fe_{60}Fa_{40}$	1.712	1.735	1.753	0.041	$78^\circ$
Hortonolite	$Fe_{40}Fa_{60}$	1.748	1.778	1.792	0.044	$69^\circ$
Ferrohortonolite	$Fe_{20}Fa_{80}$	1.786	1.822	1.833	0.047	$58^\circ$
Fayalite	$Fe_2SiO_4$	1.824	1.864	1.875	0.051	$47^\circ$
Knebelite	$(Mn,Fe)_2SiO_4$	1.80 ca.	1.84 ca.	1.85 ca.	0.05 ca.	$50^\circ$ ca.
Tephroite	$Mn_2SiO_4$	1.78	1.805	1.82	0.04 ca.	$50^\circ$ ca.
Picrotephroite	$(Mn,Mg)_2SiO_4$	1.71	1.727	1.74	0.03	$85^\circ$

*Roepperite* is a variety of knebelite containing about 17%  $MnO$  and 10%  $ZnO$ . It has  $(- )2V = 77^\circ$ ,  $N_X = 1.758$ ,  $N_Y = 1.786$ ,  $N_Z = 1.804$ ,  $N_Z - N_X = 0.046$ .

Apparently some of the iron in olivine can be oxidized, and this results in raising the indices. For example, *talasskite*<sup>42</sup> is a variety of fayalite in which about one-fifth of the iron is ferric. It has  $(- )2V = 49^\circ$ ,  $N_X = 1.870$ ,  $N_Y = 1.902$  (calc.),  $N_Z = 1.908$ ,  $N_Z - N_X = 0.038$ .

Color of olivine is commonly olive green (whence the name); by alteration it becomes yellow, brown, or red. Forsterite ( $Mg_2SiO_4$ ) is white, yellowish, or greenish; (nearly) pure  $Fe_2SiO_4$  is pale greenish yellow, but on oxidation it becomes reddish brown to black; (nearly)

<sup>42</sup> V. D. Nikitin: *Min. Abst.*, VI, 438 (1937).

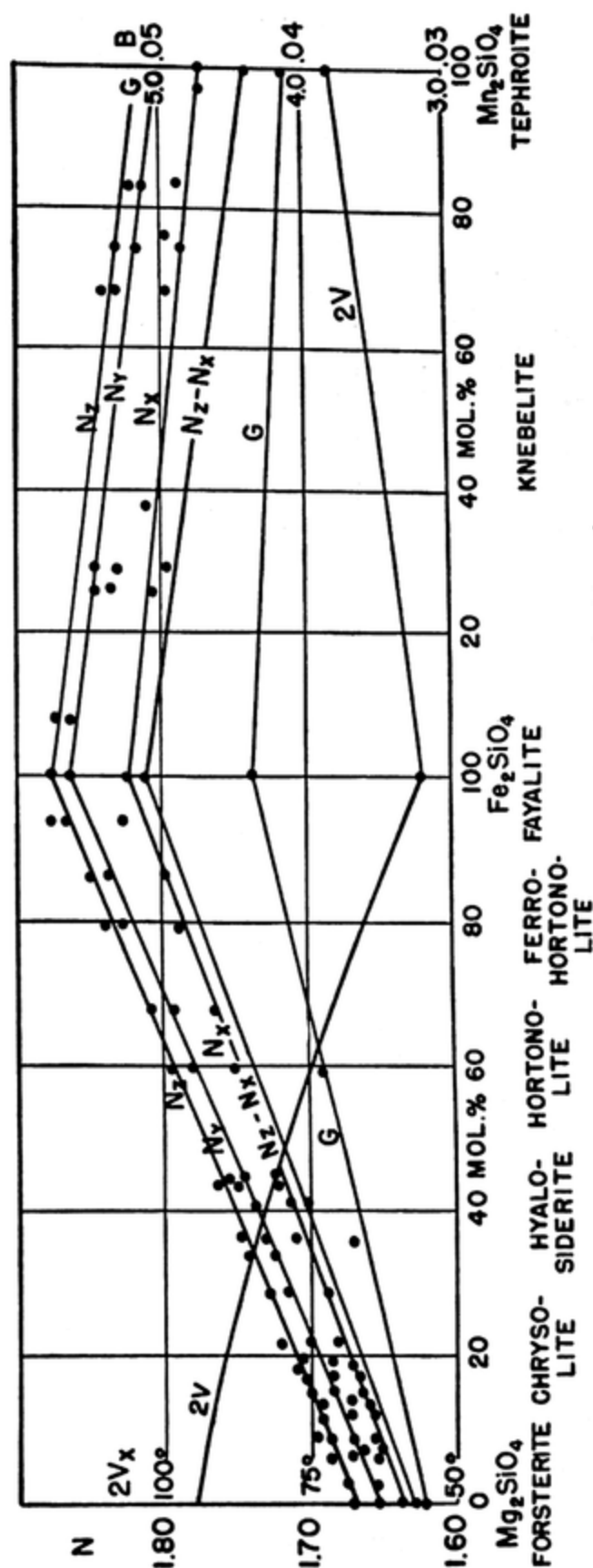


Fig. 395. Properties of the olivine double series.

pure  $Mn_2SiO_4$  is ash gray (whence the name, tephroite), grayish red, reddish brown, or rose red. Olivine is usually colorless in thin section, but fayalite may be pale yellow with  $X = Z =$  greenish yellow,  $Y =$  orange-yellow, and  $Y > X > Z$ . In thick sections tephroite has  $X =$  brownish red,  $Y =$  reddish,  $Z =$  greenish blue, and  $X < Z < Y$ .

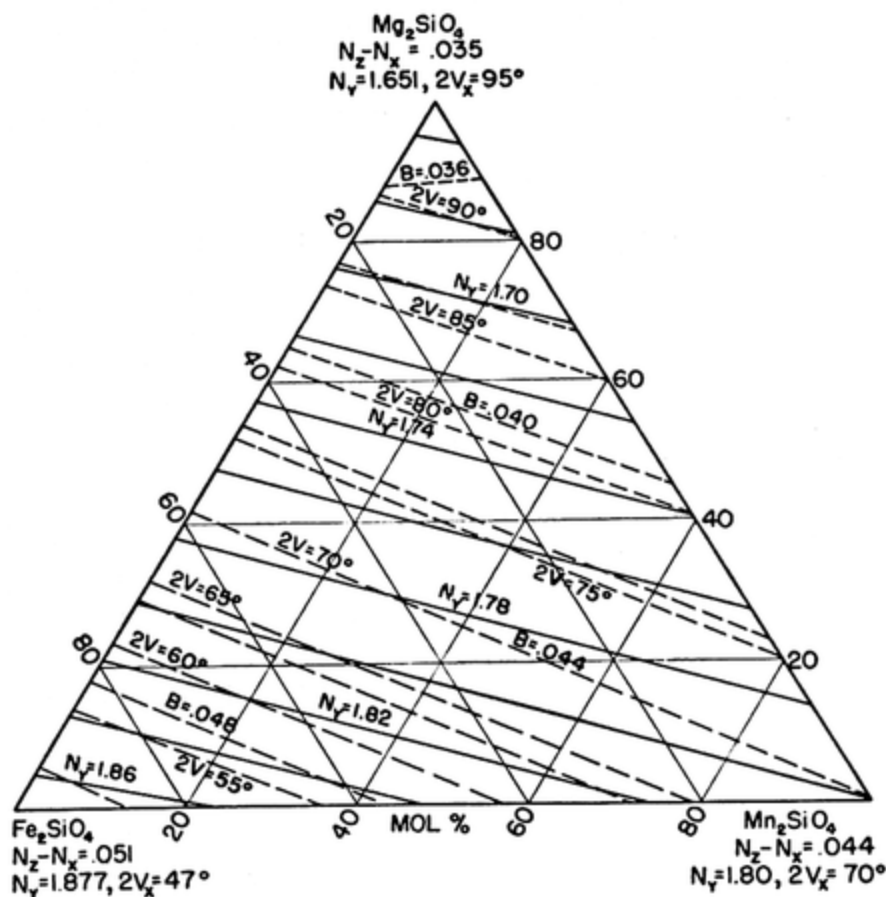


FIG. 396. Properties of olivine.

**INCL.** Common inclusions are magnetite, spinel, apatite, or liquids or gases. Movable bubbles are found at times.

**ALTER.** Olivine alters very readily; indeed it is much more commonly found altered than fresh. The commonest alteration product of olivine is either antigorite or chrysotile (sometimes both). Here the olivine is changed to a hydrous magnesium silicate with, frequently, the separation of magnetite or hematite. Along the cleavage and fracture planes, which open markedly, the antigorite or chrysotile develops in scales or fibers; finally the whole olivine crystal may be transformed to *serpentine*.<sup>43</sup> Quite often olivine alters to a mineral related to antigorite,

<sup>43</sup> Serpentine is here used as the name of a mineral aggregate composed largely of antigorite or chrysotile or both.

but containing considerable iron and showing distinctive optical properties. The new mineral may be fibrous or lamellar or compact; when compact it may have the same orientation as the original crystal of olivine. The resultant mineral may be *bowlingite*, *xylotile*, or (with nickel) *garnierite*. Serpentine in thin section is colorless to pale green with weak birefringence; bowlingite and xylotile are yellow to brown and pleochroic with strong birefringence, and garnierite is bright green.

Atmospheric weathering of olivine results in the formation of antigorite often with limonite, hematite, opal (or quartz), and carbonates.

The carbonate is often calcite, showing the removal of Mg and its replacement by Ca.



FIG. 397. Photomicrograph of olivine in thin section.

Regional metamorphism sometimes changes olivine to amphibole. This occurs only when the olivine is in contact with feldspar, and thus the pale green to colorless amphibole needles form a zone between the olivine and feldspar. Still more rarely other minerals may form from olivine: pyroxene, talc, etc.

**OCCUR.** Olivine is a common constituent of various igneous rocks, in some of which it is an essential part. See Fig. 397. It occurs in basic

igneous rocks commonly associated with augite, plagioclase, hypersthene, magnetite, etc. Also, it is not uncommon in crystalline limestone and dolomite. It is found occasionally in ore deposits. It is an essential constituent of many meteorites, forming (with enstatite, chromite, etc.) the stony portion of the mass. Fayalite is common in slags.

**DIAG.** Olivine is easily recognized. When in crystals the sections show acute-angled ends, and sections in the chief zones show extinction parallel to the elongation and the cleavages. Olivine differs from pyroxene in its poorer and unequal cleavages to which extinction is parallel. Olivine closely resembles orthorhombic humite, but the optic plane is normal to the best cleavage in olivine and parallel to the cleavage in humite. Olivine of igneous rocks is often so rich in Mg that it is optically positive.

**Monticellite** ( $\text{CaMgSiO}_4$ ) is orthorhombic dipyramidal with  $a:b:c = 0.434:1:0.576$ . Space group "Pbnm;  $a$  4.815,  $b$  11.08,  $c$  6.37 Å. U.C. 4. Crystals prismatic; also granular. Poor 010 cleavage.  $H. = 5-5.5$ .  $G. = 3.2$ .  $F. = 1498^\circ$ . Gelati-

"G. B. Brown and J. West: *Zeit. Krist.*, LXVI, 154 (1927).



nizes with HCl. The optic plane is 001;  $X = b$ .  $(- )2V = 87^\circ \text{ ca.}$ ,  $N_X = 1.641$ ,  $N_Y = 1.646$ ,  $N_Z = 1.652$ ,  $N_Z - N_X = 0.011$  (Schaller<sup>45</sup>). Samples vary in composition, and so  $2V = 75^\circ\text{--}90^\circ$ ,  $N_X = 1.639\text{--}1.66 \text{ ca.}$   $N_Y = 1.646\text{--}1.662$ ,  $N_Z = 1.652\text{--}1.68 \text{ ca.}$ , indices increasing as Fe or Mn replaces Mg. See Figs. 398 and 399. Colorless or grayish. Colorless in section. Alters to serpentine and to *fassaite*, a

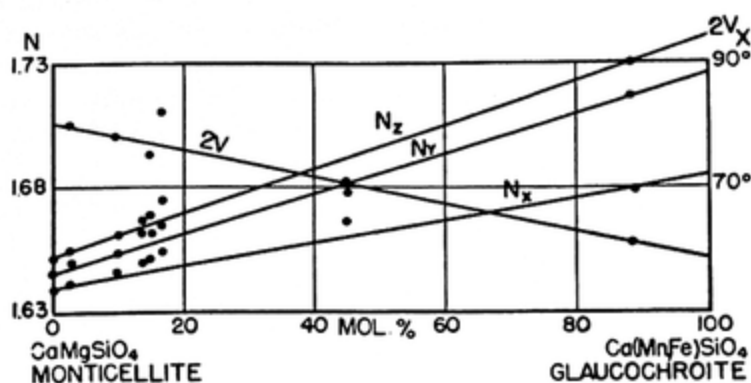


FIG. 398. Properties of the monticellite-glaucocroite series.

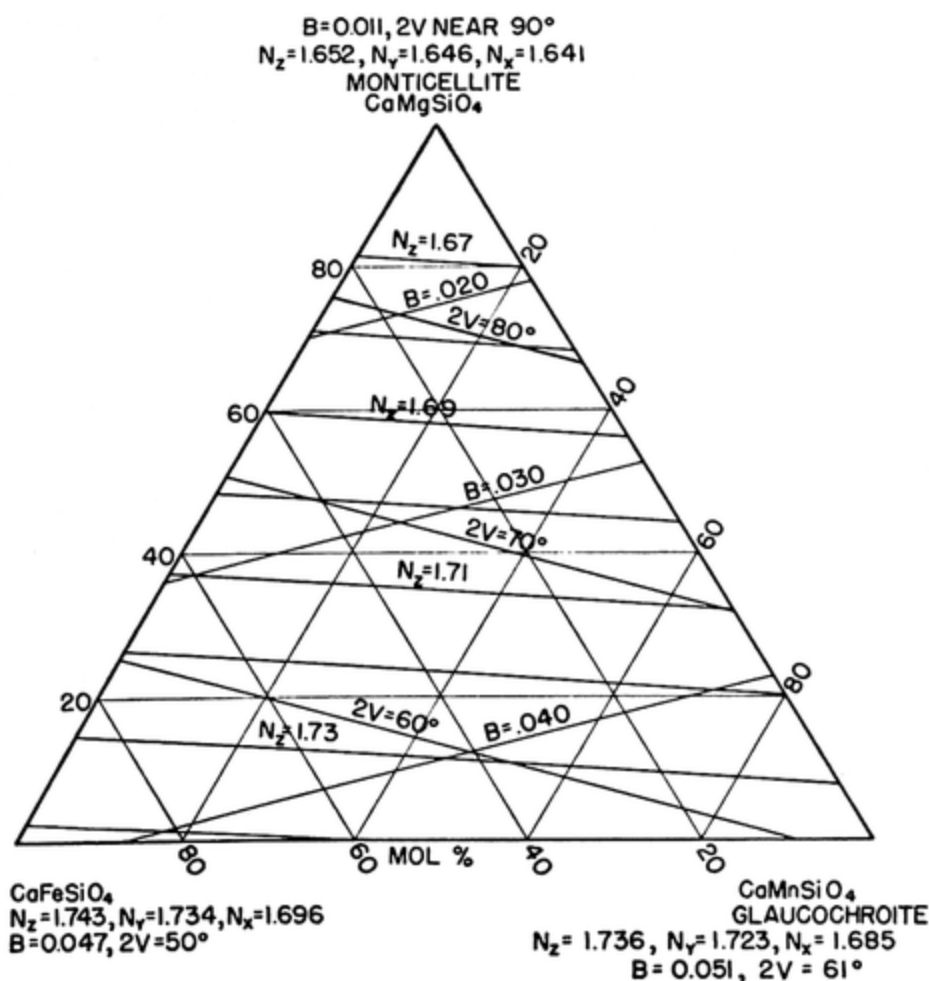


FIG. 399. Properties of the  $\text{CaMgSiO}_4\text{--CaFeSiO}_4\text{--CaMnSiO}_4$  system.

<sup>45</sup> W. T. Schaller: *Am. Mineral.*, XX, 815 (1935).

variety of augite. Found in igneous contacts with limestone, as on Monte Somma and at Magnet Cove, Arkansas.

**Glaucocroite** <sup>46</sup> ( $\text{CaMnSiO}_4$ ) is orthorhombic dipyrarnidal with  $a:b:c = 0.441:1:0.581$ . Space group  $Pbnm$ ;  $a$  4.91,  $b$  11.12,  $c$  6.49 Å. U.C. 4. Crystals prismatic, with poor 001 cleavage.  $H. = 6$ .  $G. = 3.48$ .  $F. = 1355^\circ$ . Gelatinizes with HCl. The optic plane is 001;  $X = b$ .  $(- )2V = 61^\circ$ ,  $N_X = 1.685$ ,  $N_Y = 1.723$ ,  $N_Z = 1.736$ ,  $N_Z - N_X = 0.051$  (Schaller <sup>46</sup>). Natural crystals show some variation. Color bluish green; colorless in section. Found at Franklin, New Jersey. Slags contain  $\text{CaFeSiO}_4$ ; the properties of the ternary system are shown approximately in Fig. 399.

**Larsenite** ( $\text{PbZnSiO}_4$ ) is orthorhombic <sup>47</sup> with  $a:b:c = 0.434:1:0.532$ . Crystals long prismatic with distinct (120) cleavage.  $H. = 3$ .  $G. = 5.9$ . Gelatinizes with HCl. The optic plane is 001;  $X = a$ .  $(- )2V = 80^\circ$ ,  $r > v$  distinct.  $N_X = 1.92$ ,  $N_Y = 1.95$ ,  $N_Z = 1.96$ ,  $N_Z - N_X = 0.04$ . A variety with about half the Pb replaced by Ca (called *calcium-larsenite*) has no good cleavage;  $G. = 4.42$ .  $(- )2V = 5^\circ$ ,  $N_X = 1.760$ ,  $N_Y = N_Z = 1.769$ ,  $N_Z - N_X = 0.009$ . Colorless. Found at Franklin, New Jersey.

**Larnite** <sup>48</sup> ( $\text{Ca}_2\text{SiO}_4$ ) is monoclinic with distinct 100 cleavage and common lamellar twinning on 100. Attacked slowly by water and gelatinizes readily with weak acid.  $Z = b$ ;  $X \wedge c = 13^\circ - 14^\circ$ .  $(+ )2V = \text{moderate}$ ,  $N_X = 1.707$ ,  $N_Y = 1.715$ ,  $N_Z = 1.730$ ,  $N_Z - N_X = 0.023$ . Colorless. Found in a contact zone at Larne, Ireland. Larnite is  $\beta\text{-Ca}_2\text{SiO}_4$  as found in nature.  $\alpha\text{-Ca}_2\text{SiO}_4$  is stable just below the melting point ( $2130^\circ$ ). It is hexagonal <sup>49</sup> with  $c/a = 1.296$ . Inversion to another phase on cooling may be prevented by  $\text{Mg}_2\text{SiO}_4$  in crystal solution. With 13.58  $\text{Mg}_2\text{SiO}_4$  and 5.62  $\text{Fe}_2\text{SiO}_4$  it is uniaxial positive <sup>50</sup> with  $N_O = 1.724$ ,  $N_E = 1.738$ ,  $N_E - N_O = 0.014$ . According to Bredig <sup>49</sup> the  $\alpha'$ -phase, stable above the inversion temperature ( $1420^\circ$ ) is orthorhombic <sup>51</sup> with  $a:b:c = 0.545:1:0.700$ . It has been called *bredigite*; <sup>52</sup> with 3.4 MnO, 6.9 BaO, and 6.8 MgO it has  $X = b$ ,  $Y = a$ ,  $(+ )2V = 30^\circ(-10^\circ)$ ,  $N_X = 1.712$ ,  $N_Y = 1.716$ ,  $N_Z = 1.725$ ,  $N_Z - N_X = 0.013$ ; again: a colored variety has X violet, Y and Z colorless to pale green, and  $(+ )2V = 33^\circ$ ,  $N_X = 1.725$ ,  $N_Y = 1.728$ ,  $N_Z = 1.740$ ,  $N_Z - N_X = 0.015$ .  $\gamma\text{-Ca}_2\text{SiO}_4$  (stable below  $675^\circ$ ) is monoclinic; <sup>53</sup> fibrous with perfect 010 cleavage. Optic plane normal to the fibers.  $(- )2V = ?$ ,  $N_X < 1.64$ ,  $N_Y = ?$ ,  $N_Z < 1.66$ ,  $N_Z - N_X$  distinctly less than 0.023. Again:  $\gamma\text{-Ca}_2\text{SiO}_4$  has cleavage parallel to the prism axis,  $Z \wedge c = 3^\circ$ ,  $(+ )2V = 60^\circ$ ,  $N_X = 1.642$ ,  $N_Y = 1.645$ ,  $N_Z = 1.654$ ,  $N_Z - N_X = 0.013$ . In its refringence this phase corresponds with the olivine minerals. It has been called *lime-olivine* or *shannonite*.<sup>54</sup>  $\text{Ca}_2\text{SiO}_4$  artificially forms a complete series <sup>55</sup> of mix-

<sup>46</sup> H. O'Daniel and L. Tscheischwili: *Zeit. Krist.*, CV, 273 (1944).

<sup>47</sup> C. Palache, L. H. Bauer, and H. Berman: *Am. Mineral.*, XIII, 142 and 334 (1928).

<sup>48</sup> C. E. Tilley: *Mineral. Mag.*, XXII, 77 (1929).

<sup>49</sup> M. A. Bredig: *Am. Mineral.*, XXVIII, 594 (1943).

<sup>50</sup> D. S. Belyankin and V. V. Lapin: *Min. Abst.*, X, 106 (1947).

<sup>51</sup> Measured on  $\text{Ca}_2\text{SiO}_4$  with about 8%  $\text{K}_4\text{SiO}_4$  in crystal solution. See *Am. Mineral.*, XXVIII, 594 (1943).

<sup>52</sup> C. E. Tilley and H. C. G. Vincent: *Mineral. Mag.*, XXVIII, 255 (1948).

<sup>53</sup> G. A. Rankin and F. E. Wright: *Am. Jour. Sci.*, CLXXXIX, 7 (1915).

<sup>54</sup> Name suggested by the writer in the 2nd ed. of this book in 1927, and independently by C. E. Tilley (*Geol. Mag.*, 1927, 144), after the locality (Shannon Tier, Tasmania), where it was said to be found by F. P. Paul: *Tsch. Min. Pet. Mit.*, 1906, 309.

<sup>55</sup> N. A. Toropov and P. F. Konovalov: *Min. Abst.*, X, 265 (1948).

crystals with  $Ba_2SiO_4$ , the indices and specific gravity showing a regular increase from  $G. = 3.28$ ,  $N_X = 1.717$ ,  $N_Z = 1.755$  ( $Ca_2SiO_4$ ) to  $G. = 5.2$ ,  $N_X = 1.810$ ,  $N_Z = 1.830$  ( $Ba_2SiO_4$ ).

**Merwinite**<sup>56</sup> ( $Ca_3MgSi_2O_8$ ) is monoclinic with perfect 010 cleavage. Structure<sup>57</sup> like that of perovskite with pseudo-cell edge of 3.76 Å.  $H. = 6$ .  $G. = 3.15$ . Fusible. Gelatinizes with HCl. Multiple twinning common with  $c$  as twinning axis and 110 as composition plane, the twins forming an angle of 43°; also twinning on 100. The optic plane is normal to 010;  $X \wedge c = 36^\circ$ .  $(+)2V = 70^\circ$  ca.,  $N_X = 1.706$ ,  $N_Y = 1.712$ ,  $N_Z = 1.724$ ,  $N_Z - N_X = 0.018$ . Colorless. Found in contact zones, as at Scawt Hill, Ireland; near Neihart, Montana; and at Crestmore, California. Also found in slags.

**Tinzenite**<sup>58</sup> ( $H_2Ca_3Al_4Mn^{IV}_4Si_8O_{32}$ ) is triclinic with  $a:b:c = 0.799:1:1.454$ ,  $\alpha = 136^\circ 57'$ ,  $\beta = 105^\circ 28'$ ,  $\gamma = 87^\circ 29'$ . Perfect 100 cleavage. Platy.  $G. = 3.286$ . The optic plane is near 010;  $Z' \wedge c = 9-10.5^\circ$ .  $(-)2V = 63^\circ$ ,  $N_X = 1.693$ ,  $N_Y = 1.701$ ,  $N_Z = 1.704$ ,  $N_Z - N_X = 0.011$ . Color yellow, orange-red, or pink with  $X$  = pale yellowish green,  $Y$  = pale greenish,  $Z$  = colorless. Found in ore deposits in Switzerland and Italy. Closely related to thulite in composition and properties.

## AXINITE

TRICLINIC PEDIAL  $HCa_2(Mn,Fe)BaAl_2Si_4O_{16}$

$a:b:c = 0.779:1:0.973$        $\alpha = 91^\circ 52'$        $\beta = 98^\circ 9'$        $\gamma = 77^\circ 19'$

COMP. Axinite often contains a little  $Fe^{III}$ , Mg, etc.

STRUC. Space group<sup>59</sup>  $P1$ ;  $a$  7.151,  $b$  9.184,  $c$  8.935 Å. U.C. 2.

PHYS. CHAR. Crystals usually wedge-shaped (whence the name) with good 100, and interrupted 001, 110, and 011 cleavages.  $H. = 6.5-7$ .  $G. = 3.25-3.31$ .  $F. = 2$  with intumescence. Insoluble in acid.

OPT. PROP. All the optic properties (including optic orientation) vary notably with variations in composition, but precise correlations are not yet possible—perhaps partly because variations (for example, of the optic axis) may be found in a single crystal. The negative acute bisectrix  $X$  is about normal to  $\bar{1}11$ ; but for  $X$ ,  $\phi = -24^\circ$  to  $-42^\circ$  and  $\rho = 55^\circ$  to  $60^\circ$ ; for  $Y$ ,  $\phi = 79^\circ$  to  $54^\circ$  and  $\rho = 72^\circ$  to  $81^\circ$ ; for  $Z$ ,  $\phi = 180^\circ$  to  $158^\circ$  and  $\rho = 42^\circ$  to  $32^\circ$ . See Fig. 400.  $(-)2V = 70^\circ$  to  $83^\circ$  (rarely near  $90^\circ$ ),  $r < v$ .  $N_X = 1.676-1.690$ ,  $N_Y$

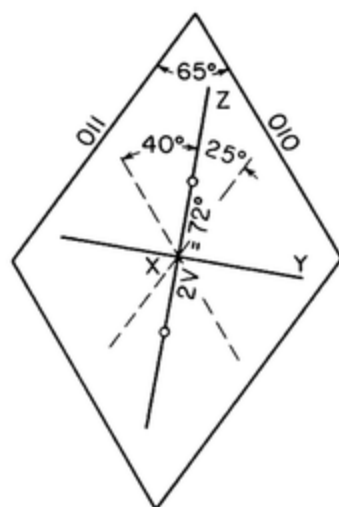


FIG. 400. Approximate optic orientation of axinite in a section parallel to  $\bar{1}11$ .

<sup>56</sup> E. S. Larsen and W. F. Foshag: *Am. Mineral.*, VI, 143 (1921); J. Phemister: *Mineral. Mag.*, XXVI, 225 (1942).

<sup>57</sup> H. J. Goldschmidt and J. R. Rait: *Nature*, CLII, 356 (1943).

<sup>58</sup> R. L. Parker: *Schw. Min. Pet. Mit.*, XXVIII, 475 (1948).

<sup>59</sup> M. A. Peacock: *Am. Mineral.*, XXII, 588 (1937).

= 1.684–1.698,  $N_z = 1.685$ –1.699,  $N_z - N_x = 0.007$ –0.013 (even 0.019—Goldschmidt<sup>60</sup>). For an axinite with 5.83 FeO, 4.42 MnO, and 0.83 MgO Neumann<sup>61</sup> reports:  $(- )2V = 76^\circ$ ,  $N_x = 1.676$ ,  $N_y = 1.684$ ,  $N_z = 1.689$ ,  $N_z - N_x = 0.013$ ,  $G. = 3.3$ .

In blue axinite the optic angle attains  $83^\circ$  (and even  $90^\circ$ ). In manganaxinite there is distinct crossed dispersion; in feraxinite the axial dispersion is scarcely perceptible in oil, but marked in air, whereas the horizontal and inclined dispersions are distinct, while crossed dispersion is nearly zero.

Color brown, gray, dull blue; manganaxinite is yellow to greenish yellow; pleochroism is lacking or weak in thin section, but very distinct in thick sections. Absorption  $Y > X > Z$ . Illustrations follow:

Sections 0.02 mm. thick	Sections 3 mm. thick
X = Colorless, pale yellow	Cinnamon brown, clear yellow
Y = Pale violet, clear yellow, sky blue	Deep violet, sulfur yellow, deep blue
Z = Colorless, pale greenish	Olive yellow, colorless

The axes of maximum, median, and minimum absorption do not coincide with X, Y, Z; if they are, respectively, D, E, F, then: <sup>62</sup>

$D \wedge X = 79^\circ 2'$	$E \wedge X = 11^\circ 24'$	$F \wedge X = 86^\circ 41'$
$D \wedge Y = 10^\circ 58'$	$E \wedge Y = 100^\circ 57'$	$F \wedge Y = 90^\circ 36'$
$D \wedge Z = 90^\circ 0'$	$E \wedge Z = 93^\circ 8'$	$F \wedge Z = 3^\circ 8'$

**OCCUR.** Axinite is usually a product of fumarolic action in contact zones; it is also found in veins. It is known at St. Cristophe, France; Striegau, Silesia; Baveno, Italy; Coquimbo, Chile; Franklin, New Jersey, etc.

**DIAG.** Its crystal form is distinctive; the relief is high; the pleochroic colors are notable in thick sections.

### (a) WITHOUT ADDITIONAL ANIONS—HYDROUS

**Hillebrandite** ( $\text{Ca}_2\text{SiO}_4 \cdot \text{H}_2\text{O}$ ) is orthorhombic; crystals fibrous with prismatic cleavages.  $H. = 5.5$ .  $G. = 2.69$ .  $F. = \text{diff. to white glass}$ . Soluble in HCl. The optic plane is (apparently) 010;  $Z = c$ .  $(- )2E = 70^\circ$ ,  $r < v$  strong.  $N_x = 1.605$ ,  $N_y = 1.61 \text{ ca.}$ ,  $N_z = 1.612$ ,  $N_z - N_x = 0.007$ . Color porcelain white or greenish; colorless in section. Found with carbonates, garnet, and wollastonite in a contact zone at Velardeña, Mexico.

<sup>60</sup> V. M. Goldschmidt: *Zeit. Krist.*, LV, 88 (1915).

<sup>61</sup> H. Neumann: *Norg. Geol. Unders.*, 162, 92 (1944). See also M. F. Beliakov: *Min. Abst.*, X, 140 (1947).

<sup>62</sup> V. Lang: *Sitz. Akad. Wiss. Wien, Math. Kl.*, CXIX, 949 (1910).

**Orientite**<sup>63</sup> ( $Ca_4Mn'''_4Si_5O_{20} \cdot 4H_2O$ ) is orthorhombic with  $a:b:c = 0.672:1:0.792$ . Crystals prismatic or {010} tablets with poor 110 cleavage.  $H. = 4.5-5$ .  $G. = 3.05$ .  $F. = 6$ . Soluble in HCl. The optic plane is 001;  $X = a$ .  $(+)2V = 67^\circ$ ,  $r < v$  very strong.  $N_X = 1.758$ ,  $N_Y = 1.776$ ,  $N_Z = 1.795$ ,  $N_Z - N_X = 0.037$ . Color dark brown with  $X = \text{red-brown}$ ,  $Y = \text{yellow}$ ,  $Z = \text{brownish yellow}$ , and  $X > Z > Y$ . Found in ore deposits in the Oriente province of Cuba.

**Cerite**<sup>64</sup>  $[(Ce, Y, Pr, Ca)_4Si_3O_{12} \cdot H_2O?]$  is of doubtful formula. Al is important according to Hanson and Pearce.<sup>65</sup> It is orthorhombic with  $a:b:c = 0.999:1:0.813$ . Crystals short prismatic, highly modified, without cleavage.  $H. = 5.5$ .  $G. = 4.65-4.91$ .  $F. = 7$ . Gelatinizes with HCl. Optic orientation unknown.  $(+)2V = 0^\circ-25^\circ$ ,  $N_X = 1.81-1.815$ ,  $N_Y = 1.815-1.818$ ,  $N_Z = 1.820-1.825$ ,  $N_Z - N_X = 0.002-0.015$ . Again:<sup>66</sup>  $(+)2V = 11^\circ$ ,  $N_X = 1.810$ ,  $N_Z = 1.825$ ,  $N_Z - N_X = 0.015$ . Color brown, red, gray; pleochroic only in thick sections with  $X = \text{nearly colorless}$ ,  $Y = ?$ ,  $Z = \text{pale reddish}$ . Found in gneiss with allanite, etc., as at Bastnäs, Sweden; also in aplites near granite, as at Jamestown, Colorado.

**Foshagite**<sup>67</sup> ( $H_2Ca_6Si_3O_{12} \cdot 2H_2O?$ ) is orthorhombic. Fibrous masses.  $H. = 3$ .  $G. = 2.67$ .  $F. = 7$ . Gelatinizes in HCl.  $Z = c$  (elongation).  $(-)2V = 60^\circ$ ,  $N_X = 1.597$ ,  $N_Y = 1.603$ ,  $N_Z = 1.605$ ,  $N_Z - N_X = 0.008$ . White. Found in veins, as at Crestmore, California.

**Iddingsite**<sup>68</sup> ( $H_4MgFe_2Si_3O_{12} \cdot 2H_2O?$ ) is orthorhombic and pseudomorphous after olivine. Lamellar with distinct 100, 001, and 010, and poor (101) cleavages.  $H. = 3$ .  $G. = 2.5-2.84$ . Attacked by HCl, which abstracts the iron. The optic plane is 010;  $X = a$ . The mineral must vary decidedly in composition since the optic properties show wide variations, as illustrated in the table below.

Sign	2V	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$	Locality
—	$35^\circ-42^\circ$	1.608	1.650	1.655	0.047	Race Creek, Colo.
—	$25^\circ-45^\circ$	1.674	1.715	1.718	0.044	La Jara Creek, Colo.
—	$20^\circ-25^\circ$	1.70	1.73	1.74	0.04	Gato Creek, Colo.
+	Large	1.70	1.72	1.74	0.04	Uncomp. Quad.,* Colo.
—	Large	1.71	1.74	1.76	0.05	Wicker Mt., Colo.
—	$42^\circ$	1.723	1.745	1.765	0.042	Carmelo Bay, Calif.
—	$60^\circ-90^\circ$	1.792	1.846	1.864	0.072	Brazos River, N. Mex.
+	$80^\circ \text{ ca.}$	1.792	1.827	1.864	0.072	Brazos River, N. Mex.

\* Uncompahgre quadrangle.

Dispersion strong,  $r < v$  over  $X$ . Color deep reddish brown to ruby red with more or less pleochroism (least in basal sections) and  $X < Y < Z$ . It is an alteration product of olivine, optically much like bowlingite. Found at Race Creek and Wicker Mt., Colorado; Carmelo Bay, California, etc.

<sup>63</sup> D. F. Hewett and E. V. Shannon: *Am. Jour. Sci.*, CCI, 491 (1921).

<sup>64</sup> E. N. Goddard and J. J. Glass: *Am. Mineral.*, XXV, 381 (1940).

<sup>65</sup> R. A. Hanson and D. W. Pearce: *Am. Mineral.*, XXVI, 110 (1941).

<sup>66</sup> V. Silberminz: *C. R. Acad. Sci. U.R.S.S.*, 1929A, 55.

<sup>67</sup> A. S. Eakle: *Am. Mineral.*, X, 97 (1925). V. A. Vigfusson: *Am. Jour. Sci.*, CCXXI, 67 (1931). Flint, McMurdie, and Wells: *J. Res. Nat. Bur. Stand.*, XXI, 617 (1938).

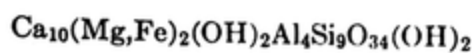
<sup>68</sup> C. S. Ross and E. V. Shannon: *Proc. U. S. Nat. Mus.*, LXVII, Art. 7 (1925).

**Chapmanite**<sup>69</sup> ( $\text{Fe}_5\text{Sb}_2\text{Si}_5\text{O}_{20} \cdot 2\text{H}_2\text{O}$ ) is orthorhombic; crystals lath-shaped.  $G. = 3.58$ .  $Z$  parallel to elongation.  $(- )2V = ?$ ,  $N_X = 1.85$ ,  $N_Y = ?$ ,  $N_Z = 1.96$ ,  $N_Z - N_X = 0.11$ . Color olive green. Found in silver ore near Cobalt, Ontario.

**Epistolite**<sup>70</sup> ( $\text{H}_3\text{Na}_6\text{Cb}_3\text{Si}_5\text{TiO}_{24} \cdot 2\text{H}_2\text{O}$ ?) is monoclinic with  $a:b:c = 0.803:1:1.206$ ,  $\beta = 105^\circ 48'$ . Crystals 001 plates with perfect 001 and good 110 cleavages.  $H. = 1-1.5$ .  $G. = 2.89$ .  $Y = b$ ;  $Z \wedge c = -7^\circ$ , with perceptible dispersion.  $(- )2V = 80^\circ \text{ca.}$ ,  $r < v$ .  $N_X = 1.610$ ,  $N_Y = 1.650$ ,  $N_Z = 1.682$ ,  $N_Z - N_X = 0.072$ . Color white, yellow, gray; colorless in section. Found in pegmatite at Julianehaab, Greenland.

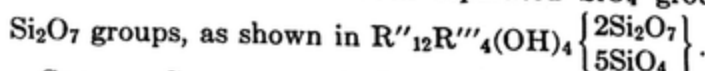
## (b) WITH ADDITIONAL ANIONS (NOT O)—ANHYDROUS

### VESUVIANITE (*Idocrase*)



DITETRAGONAL DIPYRAMIDAL  $c/a \approx 0.757$

COMP. Vesuvianite varies much in composition, with more or less Ti, Be, B,  $\text{Fe}'''$ , Na, etc. It contains<sup>72</sup> both separated  $\text{SiO}_4$  groups and also



STRUC. Space group<sup>72</sup>  $P4/nnc$ ;  $a$  15.63,  $c$  11.83 Å. U.C. 4. Crystal structure related to that of garnet.

PHYS. CHAR. Crystals often prismatic; see Fig. 401; massive. Poor 100 cleavage.  $H. = 6.5$ .  $G. = 3.33-3.45$ .  $F. = 3$  with intumescence. Attacked by HCl.

OPT. PROP. Uniaxial negative; also biaxial with  $2E = 30^\circ-60^\circ$ , and then basal sections show sectors, often four diagonal, in each of which the optic plane is normal to the edge. The optic angle decreases with rise of temperature and sometimes with increase in pressure. Birefringence usually about 0.004.

FIG. 401. A crystal habit of vesuvianite.

*Viluite* is a rare variety which is positive and usually biaxial; it contains 2-4%  $\text{B}_2\text{O}_3$ .

Vesuvianite	$N_O = 1.705-1.736$	$N_E = 1.701-1.732$	$N_O - N_E = 0.001-0.006$
Viluite	$N_O = 1.716 \text{ ca.}$	$N_E = 1.717-1.721$	$N_E - N_O = 0.001-0.005$

Color brown to red, green, rarely yellow or blue. Streak white. The color varies chiefly with the tenor and oxidation of the iron; thus yellow crystals contain up to 1% FeO and about 4%  $\text{Fe}_2\text{O}_3$ ; brown crystals contain more than 2% FeO and about the same tenor of  $\text{Fe}_2\text{O}_3$ .

In thin section colorless, pale brown, or green, the colors often in zones or patches. Pleochroism not noticeable in thin section, but in thick plates variable, as follows:

Mass Color	X	Z
Brown	Brownish yellow to brownish gray	Yellowish brown to yellowish green
Red	Light rose-red to peach-blow red	Colorless to light gray
Green	Light flesh gray, yellow, green	Colorless to greenish yellow
Blue	Nearly colorless	Dark blue

<sup>69</sup> T. L. Walker: *U. Toronto Geol. Stud.*, 17, 5 (1924).

<sup>70</sup> O. B. Böggild: *Med. Grønland*, XXIV, 183 (1900).

<sup>71</sup> 110 of the Dana orientation is taken as 100.

<sup>72</sup> B. E. Warren and D. J. Modell: *Zeit. Krist.*, LXXVIII, 422 (1931); *Phys. Rev.*, XXXVI, 1697 (1931); also J. A. Tremblay: *J. Wash. Acad. Sci.*, XXXII, 327 (1942).



**OCCUR.** Vesuvianite is found in contact zones often with garnet, diopside, wolastonite, epidote, etc.; also in schists, gneiss, amphibolite, and even igneous rocks (pegmatite and theralite) in contact zones.

**DIAG.** It is characterized by high refringence, very weak birefringence, usual negative optic sign and elongation, prismatic form, and frequent zonal arrangement of colors. It differs from zoisite in (1) the absence of cleavage, (2) abnormal dispersion, and (3) large optic angle. It differs from melilite in higher refringence and in often having color; it differs from andalusite in higher refringence, weaker birefringence, and absence of large optic angle.

**Cappelenite**  $[Ba(Y,Ce,La)_6B_3OHSi_3B_3O_{24}]$  is hexagonal with  $c/a = 1.29$ . Crystals thick prismatic without cleavage.  $H. = 6$ .  $G. = 4.4$ .  $F. = \text{diff.}$  Soluble in HCl. Uniaxial negative with  $N_O = 1.76$  (est.),  $N_O - N_E =$  rather strong. Color greenish brown. Found in veins in syenite on the isle of Lille Arö, Norway.

**Melanocerite**  $[Ca_{16}Na_4(Y,La)_3(Zr,Ce)_6F_9Si_{12}B_3O_{57}F_3]$  is hexagonal with  $c/a = 1.26$ . Crystals tabular without cleavage; trigonal symmetry.  $H. = 5-6$ .  $G. = 4.13$ .  $F. = 7$ . Decomposed by HCl. Uniaxial negative with  $N_O = 1.73$  ca.  $N_O - N_E = 0.01$  ca. Color brown to black; pale yellow in section. Alters to a reddish-brown isotropic substance with  $N = 1.77$ . Found in veins in syenite on the isle of Kjeö, Norway.

**Caryocerite** is chemically much like melanocerite. Crystals trigonal with  $c/a = 1.18$ ; tabular rhombohedral in habit without cleavage.  $H. = 5-6$ .  $G. = 4.29$ .  $F. = 7$  with swelling. Decomposed by HCl. Isotropic (through alteration) with  $N = 1.74$  ca. Color yellow to brown in section. Found in a vein in syenite of Langesundfjord, Norway.

**Tritomite** is chemically related to melanocerite. Crystals trigonal with  $c/a = 4.45$ ; acute triangular pyramidal in habit with poor cleavage.  $H. = 5.5$ .  $G. = 4.2$ . Gelatinizes with HCl. Isotropic (through alteration) with  $N = 1.73-1.76$ . Color dark brown in mass; yellow, brown, or pink in section. Found in syenite of Langesundfjord, Norway.

**Steenstrupine**<sup>73</sup>  $[R_5(OH)Si_3O_{12}]$  is very complicated in composition, containing Ca, Na, Mn, Ce, La, Al, Fe''', Ti, P, etc. Structurally related to apatite. It is hexagonal with <sup>74</sup> $a$  10.53,  $c$  45.49 Å. Crystals rhombohedral without cleavage.  $H. = 4$ .  $G. = 3.4-3.47$ . Uniaxial negative<sup>74a</sup> with weak birefringence; also isotropic (by alteration?) and then  $G. = 3.1$ . Color dark brown to black. Streak brown. Found in sodalite syenite in the Khibina region of Russia.

## TOPAZ

ORTHORHOMBIC DIPYRAMIDAL



$$a:b:c = 0.528:1:0.955$$

**COMP.** At least one-third of the F may be replaced by OH.

**STRUC.** Space group<sup>75</sup>  $Pbnm$ ;  $a$  4.61,  $b$  8.78,  $c$  8.38 Å. U.C. 4.

**PHYS. CHAR.** Crystals usually prismatic, often vertically striated, with very perfect 001 cleavage.  $H. = 8$ .  $G. = 3.5-3.57$ , increasing with tenor of F.  $F. = 7$ . Only slightly attacked by  $H_2SO_4$ .

<sup>73</sup> H. Strunz: *Naturw.*, XXX, 65 (1942).

<sup>74</sup> H. Strunz: *N. J. Min.*, 1944A, 244; *Min. Abst.*, X, 542 (1949).

<sup>74a</sup> J. C. Moberg: *Zeit. Krist.*, XXIX, 386 (1898).

<sup>75</sup> L. Pauling: *Proc. Nat. Acad. Sci.*, XIV, 603 (1928); N. A. Alston and J. West: *Zeit. Krist.*, LXIX, 149 (1928).

OPT. PROP. The optic plane and positive acute bisectrix  $Z$  are normal to 001, the perfect cleavage.  $X = a$ . See Fig. 402.  $(+ )2V = 48^\circ - 68^\circ$ ,

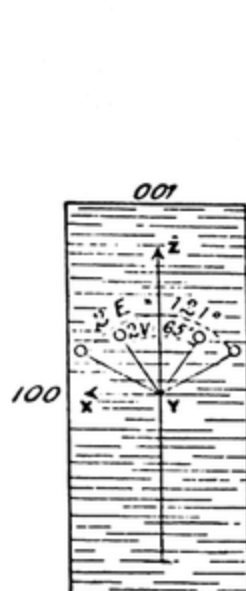


FIG. 402. The optic orientation of topaz.

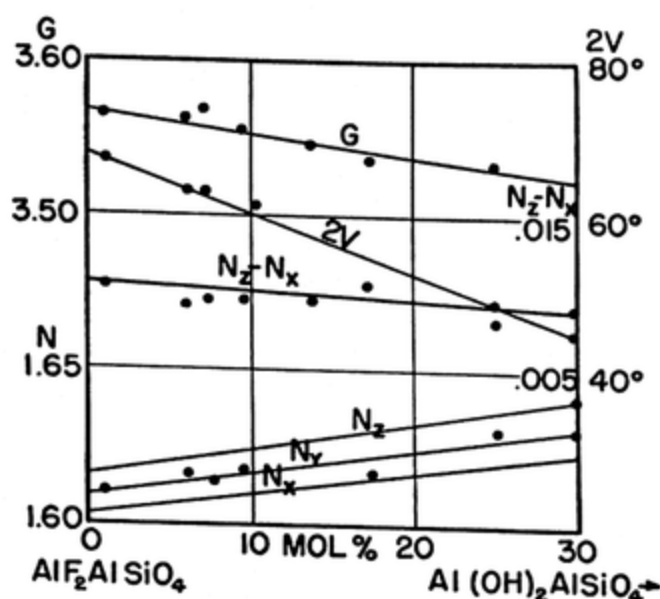


FIG. 403. Properties of topaz.

increasing with tenor of F. The refringence decreases and the birefringence slowly increases with increase in tenor of F. See Fig. 403. Data follow:

	Brewer <sup>76</sup>	Minas Gerães <sup>77</sup>	Japan <sup>77</sup>	Schneck- enstein <sup>78</sup>	Adun Tschalon <sup>77</sup>	Utah <sup>77</sup>
$\frac{100(\text{OH})}{(\text{OH} + \text{F})} =$	29.8	25.0	17.3	9.5	6.0	1.9
$(+)2E =$	$83^\circ \text{ ca.}$	$84^\circ 28'$	$119^\circ 30'$	$114^\circ 28'$	$118^\circ 46'$	$125^\circ 53'$
$(+)2V =$	$48^\circ \text{ ca.}$	$49^\circ 37'$	$64^\circ 38'$	$62^\circ 33'$	$65^\circ 30'$	$67^\circ 18'$
$N_X =$	1.629	1.6294	1.6123	1.6155	1.6133	1.6072
$N_Y =$	1.631	1.6308	1.6155	1.6181	1.6160	1.6104
$N_Z =$	1.638	1.6375	1.6229	1.6250	1.6225	1.6176
$N_Z - N_X =$	0.009	0.0081	0.0106	0.0095	0.0092	0.0104
$F - C(N_Y) =$		0.0080		0.0080	0.0077	
$G =$	3.509	3.53	3.537	3.555	3.562	3.565

Colorless, yellow, gray, greenish, reddish, bluish. Colorless in thin section. Colored crystals in thick plates are pleochroic; for example:  $X$  = brownish yellow,  $Y$  = yellowish pink,  $Z$  = violet pink.

<sup>76</sup> J. T. Pardee, J. J. Glass, and R. E. Stevens: *Am. Mineral.*, XXII, 1058 (1937).

<sup>77</sup> S. L. Penfield and J. C. Minor, Jr.: *Am. Jour. Sci.*, CXLVII, 387 (1894).

<sup>78</sup> A. Mülheims: *Zeit. Krist.*, XIV, 225, 226 (1888).

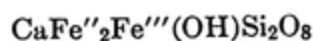
**INCL.** Liquid inclusions common, said to be  $H_2O$  or  $CO_2$  or hydrocarbons; they may contain unknown minute crystals. Ilmenite and hematite also found as inclusions.

**ALTER.** Topaz may alter to kaolinite or sericite.

**OCCUR.** It is found especially in contact zones and pegmatites, commonly associated with cassiterite, fluorite, tourmaline, beryl, etc.

**DIAG.** It differs from andalusite by its cleavage and smaller optic angle, from sillimanite by weaker birefringence and different cleavage direction; massive topaz differs from feldspar in higher relief, greater density and hardness, parallel extinction, and scarcity of twinning.

**ILVAITE** (*Lievrite*) ORTHORHOMBIC DIPYRAMIDAL<sup>79</sup>



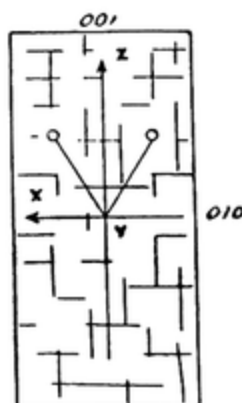
$$a:b:c = 0.666:1:0.443$$

**COMP.** Mn may proxy for  $Fe''$  to at least 9 per cent.

**STRUC.** Space group<sup>79</sup>  $Pbnm$ ;  $a$  8.82,  $b$  13.07,  $c$  5.86 Å. U.C. 4.

**PHYS. CHAR.** Crystals vertically striated prisms with distinct 001 and 010 cleavages.  $H. = 5.5-6$ .  $G. = 3.8-4.1$ .  $F. = 2.5$ . Gelatinizes with acid.

**OPT. PROP.** The optic plane and  $Z$  are normal to 001;  $X = b$ . See Fig. 404. Nearly opaque in thin section and optic data therefore incomplete.  $(- )2E = 60^\circ$  ca.,  $r < v$  strong.  $N_Y = 1.89$  (Wülfing),  $N_Z = 1.91-1.92$  (Larsen<sup>22</sup>),  $N_Z - N_X =$  strong. Also optically positive according to Böggild.<sup>79a</sup> Color iron or grayish black; intensely pleochroic in thin section; also in reflected light, as follows:



#### Transmitted Light

$X$  = Clear brown to brownish yellow  
 $Y$  = Brown, nearly opaque  
 $Z$  = Dark green to opaque

#### Reflected Light

Brown  
 Brown  
 Green

FIG. 404. The optic orientation of ilvaite.

Reflection percentages:<sup>80</sup> parallel  $a$ : red 8, orange 8.5, green 9.5; parallel  $c$ : red 5, orange 5, green 7.

**ALTER.** Ilvaite alters to limonite, etc.

**OCCUR.** It is found as a mineral of an igneous contact zone in Germany, as an alteration product of acmite in Greenland, and in iron ore in Tuscany.

**DIAG.** The crystal form is rather distinctive. In thin section it is brown (if translucent) and strongly pleochroic like enigmatite, from which it differs by its parallel extinction and maximum absorption parallel to the best cleavage.

**Cebollite**<sup>81</sup>  $[Ca_5Al_2(OH)_4Si_3O_{12}]$  is orthorhombic(?); fibrous.  $H. = 5$ .  $G. = 2.96$ .  $F. = 5$  to clear glass. Gelatinizes with  $HCl$ .  $Z$  parallel to elongation.

<sup>79</sup> B. Gossner and C. Reichel: *Cent. Min.*, 1932A, 225. See also I. Gramling-Mende: *Zent. Min.*, 1942A, 107.

<sup>79a</sup> O. Böggild: *Med. Grøn.*, XXV, 45 (1902).

<sup>80</sup> H. Schneiderhöhn and P. Ramdohr: *Lehrb. Mikrosk.*, II, 1931.

<sup>81</sup> E. S. Larsen and W. T. Schaller: *J. Wash. Acad. Sci.*, IV, 480 (1914); C. E. Tilley and H. F. Harwood: *Mineral. Mag.*, XXII, 439 (1931).

(+)2V = 58°,  $N_X = 1.595$ ,  $N_Y = 1.60$ ,  $N_Z = 1.628$ ,  $N_Z - N_X = 0.033$ ; again:<sup>82</sup> (+)2V = large,  $N_X = 1.592$ ,  $N_Y = 1.597$ ,  $N_Z = 1.630$ ,  $N_Z - N_X = 0.038$ . Colorless. An alteration product of melilite. Found in Gunnison County, Colorado, and Scawt Hill, Ireland.

**Lessingite**<sup>83</sup>  $[\text{Ca}_4(\text{Ce}, \text{Y}, \text{Er}, \text{La})_7(\text{OH}, \text{F})_6\text{Si}_6\text{O}_{24}]$  is biaxial with  $H. = 4.5$ .  $G. = 4.69$ . Greenish or reddish in mass, with vitreous luster. (-)2V = 44° ca.  $N_X = ?$ ,  $N_Y = ?$ ,  $N_Z = 1.785$ ,  $N_Z - N_X = 0.006$  ca. Found in placers in the Urals.

**Donbassite**<sup>84</sup>  $[\text{Al}_2(\text{OH})_2\text{SiO}_4]$  is orthorhombic(?) in pearly flakes resembling pyrophyllite.  $H. = 2.5$ .  $G. = 2.628$ . (+)2V = 52°,  $N_X = 1.728$ ,  $N_Y = 1.729$ ,  $N_Z = 1.735$ ,  $N_Z - N_X = 0.007$ . Color white; pearly. Found in the Donetz basin.

**Törnebohmit**<sup>85</sup>  $[(\text{Ce}, \text{La}, \text{Nd}, \text{Pr})_3(\text{F}, \text{OH})\text{Si}_2\text{O}_8]$  is granular with  $H. = 4.5$ ,  $G. = 4.9$ . (+)2V = 26°,  $r > v$  very strong. 2E = 49°,  $N_Y = 1.81$  ca.  $N_Z - N_X = 0.028-0.030$ ,  $N_Y - N_X = 0.001$  (Geijer<sup>86</sup>).  $N_X = 1.845$ ,  $N_Y = 1.852$ ,  $N_Z = 1.878$ ,  $N_Z - N_X = 0.033$  (quoted by Larsen<sup>82</sup>). Color bright olive green with  $X = \text{pink}$  or greenish yellow,  $Y = \text{bluish green}$ ,  $Z = \text{clear pink}$ , and  $X = Z < Y$ . Found with cerite, allanite, etc., at Bastnäs, Sweden.

**Roeblingite**<sup>86</sup>  $(2\text{PbSO}_4 \cdot \text{H}_{10}\text{Ca}_7\text{Si}_6\text{O}_{24})$  is probably orthorhombic; in fibrous masses.  $H. = 3$ .  $G. = 3.43$ .  $F. = 3$ . Gelatinizes with acid.  $X$  parallel to elongation. (+)2V = small.  $N_X = 1.64$ ,  $N_Y = 1.64$ ,  $N_Z = 1.66$ ,  $N_Z - N_X = 0.02$ . Colorless. Found in a contact ore deposit at Långban, Sweden, and Franklin, New Jersey.

### HUMITE FAMILY

The four minerals of the humite family are nesosilicates of magnesium with some  $\text{Mg}(\text{F}, \text{OH})_2$ . They are closely related in crystal structure but not so closely as the members of an isomorphous series or group. They are also related to olivine, as shown in the table below. Two of the minerals are orthorhombic, like olivine, and two are monoclinic. The horizontal axes are nearly equal in the four minerals, but the length of the vertical axis is related to the number of Mg atoms in the formula, as shown below:

RELATION OF OLIVINE TO THE HUMITE FAMILY<sup>87</sup>

		$a$ or $b$	$b$ or $a$	$c$	$c'$	$\beta$
Olivine	$\text{Mg}_2\text{SiO}_4$	10.21	4.755	5.98	$c' = 2 \times 2.990$	90°
Norbergite	$\text{Mg}(\text{F}, \text{OH})_2 \cdot \text{Mg}_2\text{SiO}_4$	10.2	4.70	8.72	$c' = 3 \times 2.906$	90°
Chondrodite	$\text{Mg}(\text{F}, \text{OH})_2 \cdot 2\text{Mg}_2\text{SiO}_4$	10.27	4.733	7.87	$2c' = 5 \times 2.976$	109° 2'
Humite	$\text{Mg}(\text{F}, \text{OH})_2 \cdot 3\text{Mg}_2\text{SiO}_4$	10.23	4.738	20.86	$c'/2 = 7 \times 2.980$	90°
Clinohumite	$\text{Mg}(\text{F}, \text{OH})_2 \cdot 4\text{Mg}_2\text{SiO}_4$	10.27	4.745	13.68	$c' = 9 \times 2.984$	100° 50'

<sup>82</sup> E. S. Larsen and E. A. Goranson: *Am. Mineral.*, XVII, 343 (1932).

<sup>83</sup> V. Silberminz: *N. Jahrb. Min.*, I, 123 (1930).

<sup>84</sup> E. K. Lazarenko: *Min. Abst.*, VIII, 53 (1941).

<sup>85</sup> P. Geijer: *Sver. Geol. Unders.*, Årsbok XIV, No. 6 (1920).

<sup>86</sup> R. Blix: *Am. Mineral.*, XVI, 455 (1931).

<sup>87</sup> In order to show the relations between olivine and the humite minerals,  $a$  and  $b$  axes are interchanged for olivine, norbergite, and humite.  $c'$  is the distance between opposite 001 faces of the unit cell, being the same as  $c$  in orthorhombic crystals and equal to  $c \sin \beta$  in monoclinic crystals.

**Norbergite**<sup>88</sup>  $[Mg(F,OH)_2 \cdot Mg_2SiO_4]$  is orthorhombic dipyramidal with  $a:b:c = 0.461:1:0.855$ . Space group<sup>89</sup>  $Pbnm$ ;  $b$ ,  $a$ ,  $c$  given above. U.C. 4.  $H. = 6.5$ .  $G. = 3.14$ . Gelatinizes with HCl.  $(+ )2V = 44^\circ - 50^\circ$ ,  $N_X = 1.563$ ,  $N_Y = 1.567$ ,  $N_Z = 1.590$ ,  $N_Z - N_X = 0.027$ . Found in ore deposits at Norberg, Sweden.

**CHONDRODITE**

MONOCLINIC PRISMATIC

 $Mg(F,OH)_2 \cdot 2Mg_2SiO_4$  $a:b:c = 2.170:1:1.663$      $\beta = 109^\circ 2'$ 

**COMP.** Fe can proxy for Mg at least to 6 per cent;<sup>88</sup> F and OH form a complete series. A little Ti, Al, Fe''', Mn, Na may be present.

**STRUC.** Space group<sup>89</sup>  $P2_1/c$ .  $a$ ,  $b$ ,  $c$  given above. U.C. 2.

**PHYS. CHAR.** Crystals often {010} tablets, varied in habit, with poor 001 cleavage. Multiple twinning on 001.  $H. = 6-6.5$ .  $G. = 3.1-3.2$ .  $F. = 7$ . Gelatinizes with HCl.

**OPT. PROP.** The optic plane and Z are normal to 010;  $X \wedge a = -22^\circ$  to  $-30^\circ$ . See Fig. 405. Indices vary with variations in tenor of Fe'', Fe''', Ti, Mn, OH, etc. Two types are distinguished in Sweden; one yellow and one brown—the latter perhaps due to oxidation of iron. Very weak crossed dispersion, and  $r > v$  weak. Optically positive with large optic angle (also<sup>88</sup> negative?). Data follow (unfortunately often on unanalyzed samples):

Type	2V	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$	$X \wedge a$	Authority
Franklin	(- )Large	1.594	1.607	1.619	0.025	?	Larsen <sup>88</sup>
Yellow	{ (+ ) $85^\circ - 90^\circ$	1.592	1.602	1.621	0.029	?	Rankama <sup>90</sup>
		1.601		1.637	0.036	$27^\circ 12'$	Barth <sup>91</sup>
		1.613	1.623	1.643	0.030	?	Thiele <sup>92</sup>
Brown	{ (+ ) $71^\circ$	1.619	1.630	1.650	0.031	?	Rankama <sup>90</sup>
		1.635	1.645	1.663	0.028	$26^\circ$	Larsen <sup>88</sup>
		1.643	1.655	1.670	0.027	?	Gillson <sup>93</sup>

The approximate relations between properties and composition are shown in Fig. 406.

Color yellow, brown, red; in thin section colorless to brown with  $X =$  pale golden yellow, brownish yellow, or reddish brown,  $Y =$  very pale yellow, yellowish green, or reddish brown,  $Z =$  colorless, pale yellow, pale green, or pale brown, and  $X > Y > Z$ .

**ALTER.** The brown type is more altered than the yellow; alteration may yield antigorite, brucite, magnesite, etc.

**OCCUR.** Chondrodite is found in contact zones in limestone or dolomite, and also in veins. Found at Vesuvius; Pargoes, Finland; Brewster, New York, etc.

**DIAG.** It differs in extinction angle from other members of the humite family; the twinning and color distinguish it from olivine.

<sup>88</sup> E. S. Larsen: *Am. Mineral.*, XIII, 354 (1928).

<sup>89</sup> W. H. Taylor and J. West: *Zeit. Krist.*, LXX, 461 (1929); *Proc. Roy. Soc.*, CXVII, 517 (1928).

<sup>90</sup> K. Rankama: *Bull. Comm. Géol. Finlande*, No. 123, p. 81 (1938).

<sup>91</sup> T. Barth: *Norsk Geol. Tidssk.*, VIII, 94 (1924).

<sup>92</sup> E. Thiele: *Chem. Erde*, XIII, 64 (1940).

<sup>93</sup> J. L. Gillson: *Am. Mineral.*, XI, 284 (1926).

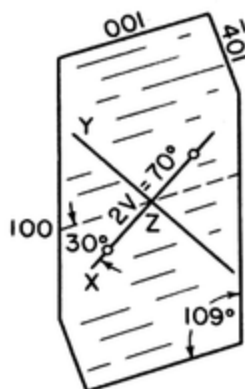


FIG. 405. The optic orientation of chondrodite.

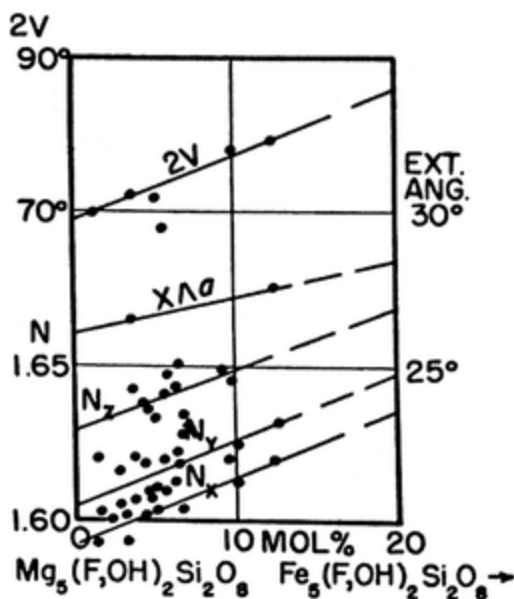
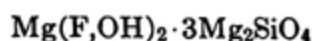


FIG. 406. Properties of chondrodite.

## HUMITE

ORTHORHOMBIC DIPYRAMIDAL



$$a:b:c = 0.463:1:2.039$$

COMP. Fe can proxy for Mg to at least 8 per cent; Ti, Fe<sup>III</sup>, Al, Mn may be present.

STRUC. Space group <sup>89</sup> *Pbnm*; *b*, *a*, *c* given above. U.C. 4.

PHYS. CHAR. Crystals small complex 100 or 001 tablets with poor 001 cleavage.

H. = 6. G. = 3.2–3.3. F. = 7. Gelatinizes with HCl.

OPT. PROP. The optic plane and Z are normal to 010; X = *a*. See Fig. 407. Dispersion *r* > *v* weak. Data follow:

FeO + MnO	(+)2V	N <sub>X</sub>	N <sub>Y</sub>	N <sub>Z</sub>	N <sub>Z</sub> - N <sub>X</sub>	Authority
2.35	?	1.621	1.627	1.649	0.028	Larsen <sup>88</sup>
5.37	69°	1.623	1.634	1.655	0.032	Rankama <sup>90</sup>
12.43	67° 54'	?	1.643	?	?	Lacroix
8.43 (+2.66 Fe <sub>2</sub> O <sub>3</sub> )	68°	1.643	1.653	1.675	0.032	Rankama <sup>90</sup>

Color white, yellow, brown; in thin section colorless or pleochroic with X = pale to dark golden yellow, Y = pale yellow, Z = golden yellow, and X > Z > Y.

OCCUR. Humite is found in contacts in limestone or dolomite; also in veins. Found at Filipstad, Sweden; Brewster, New York; etc.

DIAG. The extinction angle measured on the cleavage (or the lamellar twinning) in a section normal to Z, the acute bisectrix, is 0° in humite, 7°–15° in clinohumite, 20° in titanclinohumite, and 26°–30° in chondrodite. The lamellar twinning is not present in humite. Humite has the same pleochroic colors as staurolite, but the golden-yellow color is parallel to Z in staurolite and parallel to X in humite. Colorless humite differs from forsterite and chrysolite in having a smaller optic angle, lower refringence, and the optic plane parallel rather than normal to the best cleavage. Of course it also differs in composition.



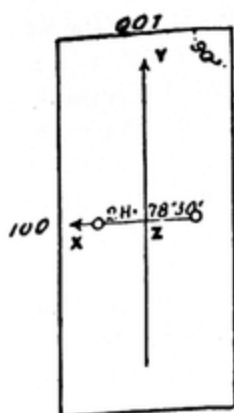


FIG. 407. The optic orientation of humite.

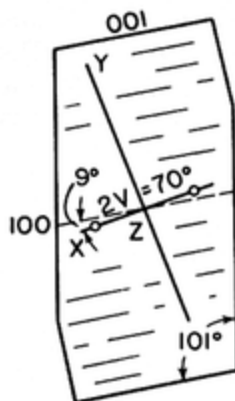


FIG. 408. The optic orientation of clinohumite.

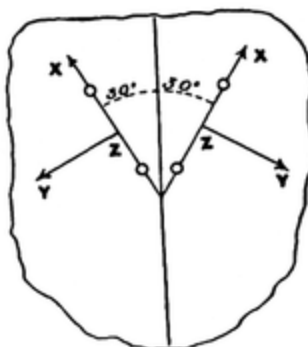


FIG. 409. The optic orientation in twinned chondrodite.

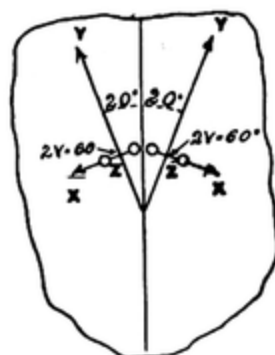
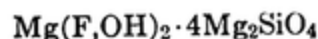


FIG. 410. The optic orientation in twinned titanclino-humite.

**CLINOHUMITE****MONOCLINIC PRISMATIC**

$$a:b:c = 0.462:1:1.332 \quad \beta = 100^\circ 50'$$

COMF. Fe, Mn, Pb, Zn may proxy for Mg;  $\text{Fe}^{+++}$ , Ti, Na, etc., may be present; Ti becomes important (5% ca.) in the variety *titanclino-humite*.

STRUC. Space group  $^{94}P2_1/c$ ;  $a$ ,  $b$ ,  $c$  given above. U.C. 2.

PHYS. CHAR. Crystals complex and varied with 001 cleavage, not prominent in sections. Lamellar twinning on 001.  $H. = 6$ .  $G. = 3.17-3.25$ .  $F. = 7$ . Gelatinizes with HCl.

OPT. PROP. The optic plane and  $Z$  are normal to 010;  $X \wedge a = 7^\circ-20^\circ$ . See Figs. 408-410. Weak crossed dispersion and  $r > v$  very weak. Data follow:

FeO + MnO	TiO <sub>2</sub>	(+) $2V$	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$	$X \wedge 001$	Authority
4.83	?	Near $90^\circ$	1.625	1.638	1.653	0.028	?	Larsen <sup>88</sup>
5.64	?	$74^\circ$	1.632	1.644	1.664	0.032	?	Larsen <sup>88</sup>
15.44	0.06	$76^\circ$	1.652	1.663	?	?	$12^\circ-15^\circ$	Larsen <sup>88</sup>
5.18	1.92	$62^\circ$	1.664	1.673	1.698	0.034	$7.5^\circ$	Larsen <sup>88</sup>
?	?	Near $90^\circ$	1.655	1.678	1.700	0.045	?	Lindberg <sup>95</sup>
6.20	5.20	$58^\circ$	1.691	1.700	1.724	0.033	?	Quervain <sup>96</sup>

Color brown, yellow, white; in thin section colorless or pleochroic with  $X$  = pale golden or brownish yellow,  $Y$  = very pale yellow or green or colorless,  $Z$  = pale yellow or colorless and  $X > Z > Y$ . With Ti the color becomes brownish red with  $X$  = deep reddish yellow to blood red,  $Y = Z$  = orange yellow, and  $X > Y > Z$ .

OCCUR. Clinohumite is found in contact zones in dolomite, and also in veins, as well as talc schist and serpentine. Known at Pargas, Finland; Brewster, New York, etc.

DIAG. See humite.

**Hodgkinsonite**  $[\text{MnZn}_2(\text{OH})_2\text{SiO}_4]$  is monoclinic with  $a:b:c = 1.538:1:1.108$ ,  $\beta = 95^\circ 25'$ . Crystals pyramidal with perfect 001 cleavage.  $H. = 4-4.5$ .  $G.$

<sup>94</sup> W. H. Taylor and J. West: *Proc. Roy. Soc.*, CXVIA, 517 (1928).

<sup>95</sup> M. L. Lindberg: *Bull. Geol. Soc. Am.*, LVII, 1213 (1946).

<sup>96</sup> F. de Quervain: *Schw. Min. Pet. Mit.*, XVIII, 591 (1938). Contains 4.69  $\text{Fe}_2\text{O}_3$ .

= 3.91. F. = easy after decrepitation. Gelatinizes with HCl. The optic plane is 010;  $Z \wedge c = 38^\circ$ —Z emerges from a cleavage plate.  $(- )2V = 50^\circ$  to  $60^\circ$ ,  $r > v$  distinct.  $N_X^{97} = 1.724$ ,  $N_Y = 1.742$ ,  $N_Z = 1.746$ ,  $N_Z - N_X = 0.022$ . Color pink to brown; pleochroic with X = Z = lavender, Y = almost colorless. Found with willemite and franklinite at Franklin, New Jersey.

**Alleghanyite**<sup>98</sup>  $[Mn_5(OH,F)_2Si_2O_8]$  is monoclinic with  $\beta = 90^\circ$  ca. related in structure to chondrodite. No cleavage. Common lamellar twinning with symmetrical extinction at  $22^\circ$ . H. = 5.5. G. = 4.02. The optic plane and Z are normal to 010;  $X \wedge a = +22^\circ$  to  $+35^\circ$ .  $(- )2V = 72^\circ$ ,  $r > v$ .  $N_X = 1.756$ ,  $N_Y = 1.780$ ,  $N_Z = 1.792$ ,  $N_Z - N_X = 0.036$ . Colorless in thin section, but pleochroic, pink to buff in thick plates. Found in veins with tephroite, spessartite, rhodonite, etc., at Bald Knob, North Carolina.

**Leucophenicit**  $[Mn_7(OH)_2Si_3O_{12}]$  is monoclinic with  $a:b:c = 1.105:1:2.314$ ,  $\beta = 103^\circ 16'$ . Crystals elongated parallel to b, deeply striated; imperfect cleavage. Twinning on 001. H. = 5.5–6. G. = 3.85. F. = 3. Gelatinizes with HCl. The negative acute bisectrix X is normal to a cleavage.  $(- )2V = 74^\circ$ ,  $r > v$  weak.  $N_X = 1.751$ – $1.760$ ,  $N_Y = 1.771$ – $1.778$ ,  $N_Z = 1.782$ – $1.790$ ,  $N_Z - N_X = 0.030$  ca. Color pale purplish red; in section colorless or pale rose to colorless. Found with willemite and vesuvianite at Franklin, New Jersey.

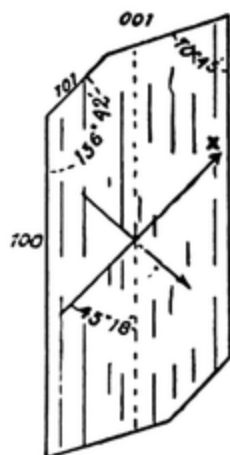


FIG. 411. The optic orientation of woehlerite.

**Woehlerite**  $[NaCa_2(Zr,Cb)FSi_2O_8]$  is monoclinic with  $a:b:c = 1.055:1:0.709$ ,  $\beta = 109^\circ 3'$ . Space group<sup>99</sup>  $P2_1$  or  $P2_1/m$ ;  $a$  10.80,  $b$  10.26,  $c$  7.26 Å. U.C. 4. Crystals prismatic and {100} tablets; twinning on 100. Distinct 010 cleavage. H. = 5.5–6. G. = 3.42. F. = 3–3.5. Soluble in HCl.  $Z = b$ ;  $X \wedge c = +45^\circ$  ca.  $(- )2V = 71^\circ$ – $79^\circ$ ,  $r < v$  distinct. See Fig. 411.  $N_X = 1.700$ ,  $N_Y = 1.716$ ,  $N_Z = 1.726$ ,  $N_Z - N_X = 0.026$ . Color light yellow to brown with X and Y = light wine yellow, Z = deep wine yellow. Found in zircon syenite near Brevik, Norway, etc.

**Spurrite**<sup>100</sup>  $(CaCO_3 \cdot 2Ca_2SiO_4)$  is monoclinic(?), with distinct 001 and poor 100 cleavages at  $79^\circ$ . Multiple twinning on 001 and on an orthodome at  $57^\circ$ . H. = 5. G. = 3. F. = 7. Effervesces and gelatinizes with HCl. The optic plane and X are normal to 010;  $Z \wedge a =$  nearly  $0^\circ$  with distinct crossed dispersion.  $(- )2V = 39.5^\circ$ ,  $r > v$  weak.  $N_X = 1.640$ ,  $N_Y = 1.674$ ,  $N_Z = 1.679$ ,  $N_Z - N_X = 0.039$ . According to Tilley<sup>101</sup> the distinct cleavage is 100,  $X = b$  and  $Y \wedge c = -33^\circ$ . Tinted or colorless in mass. Alters to afwillite. Found in contacts, as at Scawt Hill, Ireland. An artificial product<sup>102</sup> called  $\alpha$ -spurrite is orthorhombic with  $N_X = 1.665$ ,  $N_Z = 1.680$ .

**Johnstrupite**  $[(Ca,Na,Ce)_3(Al,Ti)(F,OH)Si_2O_8]$  is monoclinic with  $a:b:c = 1.623:1:1.391$ ,  $\beta = 93^\circ 4'$ . Crystals long prismatic {100} plates, vertically striated. Distinct 100 cleavage. Lamellar twinning on 100. H. = 4. G. = 3.3. F. = 3. Soluble in HCl. The optic plane is 010;  $X \wedge c = 2^\circ$ .  $(+ )2V = 70^\circ$ ,  $r > v$  strong.  $N_X = 1.661$ ,  $N_Y = 1.666$ ,  $N_Z = 1.673$ ,  $N_Z - N_X = 0.012$ . Birefringence variable,

<sup>97</sup> C. Palache: *U. S. Geol. Surv. Prof. Paper* 180 (1935).

<sup>98</sup> A. F. Rogers: *Am. Mineral.*, XX, 25 (1935).

<sup>99</sup> B. Gossner and O. Kraus: *Zeit. Krist.*, LXXXVI, 308 (1933).

<sup>100</sup> F. E. Wright: *Am. Jour. Sci.*, CLXXVI, 547 (1908).

<sup>101</sup> C. E. Tilley: *Mineral. Mag.*, XXII, 77 (1929).

<sup>102</sup> W. Eitel: *N. Jahrb. Min.*, Bl. Bd. XLVIII, 63 (1923).

about as in epidote. Color brownish green; colorless to yellow in thin section. Found at Barkevik, Norway.

**Mosandrite**  $[(Ca,Na)_{12}Ce_3(Zr,Ti,Mg)_4F_5(SiO_4)_{10}]$  is monoclinic<sup>103</sup> with  $a:b:c = 3.264:1:1.318$ ,  $\beta = (93^\circ 4')$ .  $a$  18.37,  $b$  5.63,  $c$  7.42 Å. Crystals long prismatic; distinct 100 cleavage.  $G. = 3.0$ . The optic plane is 010;  $X \wedge c = 2^\circ$ .  $(+ )2V = 74^\circ$ ,  $r > v$  strong. See Fig. 412.  $N_X = 1.646$ ,  $N_Y = 1.649$ ,  $N_Z = 1.658$ ,  $N_Z - N_X = 0.012$ . Birefringence variable, about as in epidote. Color reddish brown. Yellow to colorless in thin section. Found in pegmatite on the isles of Låven and Stokö, Norway.

**Rinkite**  $[NaCa_2(Ti,Ce)F(SiO_4)_2]$  is monoclinic<sup>103</sup> with  $a:b:c = 3.257:1:1.316$ ,  $\beta = 91^\circ 13'$ .  $a$  18.47,  $b$  5.67,  $c$  7.46 Å. U.C. 2. Crystals prismatic or {100} tablets

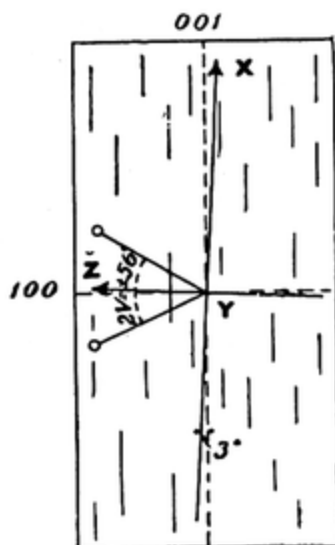


FIG. 412. The optic orientation of mosandrite.

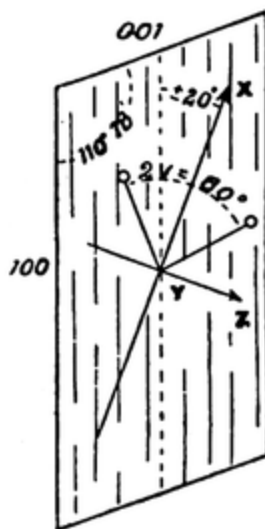


FIG. 413. The optic orientation of låvenite.

with distinct 100 cleavage. Lamellar twinning on 100.  $H. = 5$ .  $G. = 3.46$ .  $F. = 7$ . Attacked by  $H_2SO_4$ . The optic plane and  $X$  are normal to 010;  $Y \wedge c = -7.5^\circ$  with distinct dispersion.  $(+ )2V = 43^\circ$ ,  $r < v$  strong.  $N_X = 1.665$ ,  $N_Y = 1.668$ ,  $N_Z = 1.681$ ,  $N_Z - N_X = 0.016$ . Color yellow to brown; nearly colorless in thin section with  $X < Y < Z$ . Found in alkali syenite at Kangerdluarsuk, Greenland.

**Rinkolite**<sup>104</sup> is similar but the optic plane is 010;  $X \wedge c = 1.5^\circ - 3.5^\circ$ .  $(+ )2V = 45^\circ - 88^\circ$ ,  $r < v$ .  $N_X = 1.643 - 1.662$ ,  $N_Y = 1.645 - 1.667$ ,  $N_Z = 1.651 - 1.681$ ,  $N_Z - N_X = 0.008 - 0.019$ . Color brown, green, yellow. **Lovchorrite** is a colloidal, partly isotropic variety. Found on the Kola peninsula, U.S.S.R.

**Låvenite**  $[(Ca,Na)(Zr,Cb,Fe,Ti,Mn)FSiO_4]$  is monoclinic<sup>103</sup> with  $a:b:c = 1.104:1:0.725$ ,  $\beta = 110^\circ 18'$ .  $a$  10.93,  $b$  9.99,  $c$  7.18 Å. Crystals prismatic or {100} tablets with distinct 100 cleavage. Lamellar twinning on 100.  $H. = 6$ .  $G. = 3.5$ . Slowly soluble in  $HCl$ . The optic plane is 010;  $Z \wedge c = -70^\circ$ .  $(- )2V = 80^\circ$ , dispersion weak. See Fig. 413.  $N_Y = 1.750$ ,  $N_Z - N_X = 0.030$ . A variety<sup>105</sup> with 11.30  $TiO_2$  has:  $(- )2V = 73^\circ - 74^\circ$ ,  $N_X = 1.720$ ,  $N_Y = 1.746$ ,  $N_Z = 1.760$ ,  $N_Z - N_X$

<sup>103</sup> B. Gossner and O. Kraus: *Cent. Min.*, 1934A, 72.

<sup>104</sup> A. E. Fersman: *Am. Mineral.*, XI, 289 (1926); *Min. Abst.*, III, 235 (1927).

<sup>105</sup> E. I. Kutukova: *Am. Mineral.*, XXVI, 135 (1941).

= 0.040. Colorless, yellow, or brown. May be pleochroic with X = colorless to clear wine yellow, Y = colorless to greenish yellow, Z = golden or brownish yellow or orange-red. Found in syenite on the isle of Låven, Norway; in Minas Gerães, Brazil; etc.

**Hellandite**  $[\text{Ca}(\text{Al}, \text{Y}, \text{Er}, \text{Fe}''')(\text{OH})_3\text{Si}_2\text{O}_8]$  is monoclinic with  $a:b:c = 2.065:1:2.151$ ,  $\beta = 109^\circ 45'$ . Crystals {010} tablets, etc. Twinning on 001, also in bands on 100. H. = 5.5. G. = 3.35–3.70. F. = easy. Soluble in HCl. The optic plane and X are normal to 010;  $Z \wedge c = +43.5^\circ$ .  $(+ )2V = 80^\circ \text{ ca.}$   $N_Y = 1.65$  (est.),  $N_Z - N_X = 0.01 \text{ ca.}$  decreasing with alteration. Color brown to red; not pleochroic. During gradual alteration to the "metamict" state the birefringence and extinction angle ( $Z \wedge c$ ) both decrease toward zero. Found in pegmatite with tourmaline, thorite, allanite, etc., at Kragero, Norway.

**Bultfonteinite**<sup>106</sup>  $[\text{H}_2\text{Ca}_2\text{F}_2\text{SiO}_4?]$  is triclinic with  $a:b:c = 0.676:1:0.687$ ,  $\alpha = 94^\circ 17'$ ,  $\beta = 91^\circ 59'$ ,  $\gamma = 90^\circ 44'$ . Crystals acicular in radial spherulites. Lamellar twinning on 100 and on 010. Fair 100 and 010 cleavages. H. = 4.5. G. = 2.73.  $Z' \wedge c$  on 010 =  $27^\circ$  to  $29^\circ$ .  $Z'$  on 100 =  $46^\circ$  to  $48^\circ$ . For X:  $\phi = -24^\circ$ ,  $\rho = 55^\circ$ . For Y:  $\phi = -132.5^\circ$ ,  $\rho = 66^\circ$ . For Z:  $\phi = 111^\circ$ ,  $\rho = 44.5^\circ$ .  $(+ )2V = 70^\circ$ ,  $N_X = 1.587$ ,  $N_Y = 1.590$ ,  $N_Z = 1.597$ ,  $N_Z - N_X = 0.010$ . Pink in mass; colorless in section. Found as a secondary mineral in the Bultfontein mine at Kimberley, South Africa.

**Rosenbuschite**  $[(\text{Na}, \text{Ca}, \text{Mn})_3(\text{Fe}''', \text{Ti}, \text{Zr})\text{FSi}_2\text{O}_8]$  is triclinic<sup>107</sup> with  $a:b:c = 0.889:1:0.638$ ,  $\alpha = 91^\circ 21'$ ,  $\beta = 99^\circ 38.5'$ ,  $\gamma = 111^\circ 54.5'$ ;  $a$  10.12,  $b$  11.39,  $c$  7.27 Å. U.C. 4. Crystals prismatic or acicular with perfect 100 cleavage. H. = 5–6. G. = 3.3. F. = easy. Soluble in HCl. X = c (parallel to fibers),  $Z \wedge \perp 100 = 28.5^\circ$ .  $(+ )2V = 78^\circ$ ,  $r > v$ .  $N_X = 1.678$ ,  $N_Y = 1.687$ ,  $N_Z = 1.705$ ,  $N_Z - N_X = 0.027$ . Color orange or gray; weakly pleochroic in thin section in yellow with  $X < Y < Z$ . Found in syenite at Langesundsfjord, Norway.

**Guarinite**<sup>108</sup>  $[(\text{Ca}, \text{Na})_3(\text{Fe}, \text{Mn}, \text{Zr}, \text{Cb})(\text{O}, \text{OH}, \text{F})\text{Si}_2\text{O}_8]$  is triclinic with  $a:b:c = 0.943:1:0.671$ ,  $\alpha = 108^\circ 50'$ ,  $\beta = 90^\circ 29'$ ,  $\gamma = 90^\circ 8'$ ;  $a$  10.29,  $b$  10.91,  $c$  7.32 Å. U.C. 4. *Hiortdahlite* is a variety with Ti in place of Cb. Crystals {100} tablets with 110 and  $\bar{1}\bar{1}0$  cleavages nearly at  $90^\circ$ . H. = 5.5. G. = 3.2–3.5. Gelatinizes with HCl. The optic plane<sup>22</sup> is nearly parallel with  $\bar{1}\bar{1}1$ ; extinction (measured to the optic plane) is  $65^\circ$  to  $c$  on 100 and  $75^\circ$  to  $c$  on 010.  $(+ )2V = \text{near } 90^\circ$ ,  $r < v$  strong,  $N_X = 1.652$ ,  $N_Y = 1.658$ ,  $N_Z = 1.665$ ,  $N_Z - N_X = 0.013$ . Color yellow to brown with X = colorless to canary yellow, Y = yellowish, Z = wine to pale yellow. Found in syenite at Monte Somma. Differs from woehlerite and låvenite in having weaker birefringence.

**Hainite** is closely related to guarinite, but probably contains Ce. Crystals prismatic with distinct 010 cleavage and twinning on 100. H. = 5. G. = 3.18. F. = 4 ca. Decomposed by HCl. The optic plane and Z are nearly normal to 010; extinction on 100 is nearly parallel to  $c$ , on 010 it is at about  $4^\circ$  to  $c$ , and in a section normal to  $c$  at about  $16.5^\circ$  to  $b$ . Extinction imperfect due to strong dispersion.  $(+ )2V = \text{large}$ ,  $r > v$ ;  $N_Y = 1.7 \text{ ca.}$   $N_Z - N_X = 0.012$ . Color and pleochroism as in guarinite. Found in phonolite at Hohe Hain, Bohemia. Differs from guarinite in its positive elongation.

<sup>106</sup> J. Parry, A. F. Williams, and F. E. Wright: *Mineral. Mag.*, XXIII, 145 (1932).

<sup>107</sup> M. A. Peacock: *Norsk. Geol. Tidssk.*, XVII, 17 (1937).

<sup>108</sup> B. Gossner and O. Kraus: *Cent. Min.*, 1934A, 72;  $a$  and  $b$  interchanged to make  $b > a$ .

## (b) WITH ADDITIONAL ANIONS (NOT O)—HYDROUS

**McGovernite**<sup>109</sup> [(Mn,Mg,Zn)<sub>7</sub>OHAsSiO<sub>4</sub>·3H<sub>2</sub>O?] is hexagonal(?) with  $G. = 3.72$ . Perfect basal cleavage. Uniaxial positive with  $N_O = 1.754$ . Color red-brown; luster like bronze. Found in zinc-ore deposit at Sterling Hill, New Jersey.

**Gageite**<sup>97</sup> [(Mn,Mg,Zn)<sub>16</sub>(OH)<sub>8</sub>Si<sub>6</sub>O<sub>24</sub>·3H<sub>2</sub>O?] is orthorhombic in minute prismatic needles or laths.  $G. = 3.58$ .  $F. = 7$ . Soluble in dilute HNO<sub>3</sub>.  $Z$  is parallel to needles.  $(- )2V =$  moderate,  $r < v$  extreme.  $N_X = 1.723$ ;  $N_Y = 1.734$ ,  $N_Z = 1.736$ ,  $N_Z - N_X = 0.013$ . Colorless to pink. Found at Franklin, New Jersey.

**Pumpellyite**<sup>110</sup> [Ca<sub>2</sub>Al<sub>3</sub>(OH)Si<sub>3</sub>O<sub>12</sub>·H<sub>2</sub>O?] is monoclinic with  $a:b:c = 1:?:0.842$ ,  $\beta = 110^\circ$  ca. Varies in composition, containing some Fe''', Fe'', Mg, Na, etc. Fibrous or in 001 tablets with distinct 001 and poor 100 cleavages. Twinning on 001.  $H. = 5.5$ .  $G. = 3.2-3.3$ . Insoluble in HCl. There are great variations in optic properties not yet correlated with variations in composition. The optic plane is normal to 010 in some crystals, but parallel thereto in most.<sup>110</sup>  $X \wedge a = 4^\circ-32^\circ$ .  $(+)2V = 38^\circ$  ( $\perp 010$ ), with  $r > v$ , to  $80^\circ$  ( $\parallel 010$ ) with  $r < v$ , passing through  $0^\circ$  between these two cases.  $F - C$  for  $N_Y = 0.014-0.016$ . Dispersion very strong,  $r < v$  in most cases, but  $r > v$  when  $Z = b$ . Data follow:

Source	2Vz	N <sub>X</sub>	N <sub>Y</sub>	N <sub>Z</sub>	N <sub>Z</sub> - N <sub>X</sub>	X $\wedge$ a	G.	Authority
Otago	Small	1.678	1.681	1.688	0.010	?		Hutton <sup>111</sup>
California	40°	1.679	1.680	1.692	0.013	12°	3.18;3.22	Irving <sup>112</sup>
Japan	36°-40°	1.686	1.690	1.698	0.012	11°-12°		Tsuboi <sup>113</sup>
S. Africa	38°-0°-71°		1.694-1.726			4°-32°	3.23-3.32	Villiers <sup>111</sup>
Keweenaw	Large	1.698	1.700	1.708	0.010	?	3.2	Palache <sup>114</sup>
Haiti	75°-80°	1.700	1.707	1.718	0.018	59°		Burbank <sup>115</sup>
Urals	65° calc.	1.703	1.716	1.721	0.018	?		Zavaritsky <sup>116</sup>

Color bluish green or brown and strongly pleochroic with  $X =$  colorless or pale greenish yellow,  $Y =$  blue-green (rarely brownish yellow),  $Z =$  colorless or rarely brownish yellow, and  $Y > Z > X$ . Found in amygdules in basalt in Haiti and in copper mines in Michigan; in glaucophane schist at Petaluma, California; in vein quartz at Witwatersrand, South Africa, etc.

**Lotrite**<sup>117</sup> [(Ca,Mg)<sub>3</sub>(Al,Fe)<sub>4</sub>(OH)<sub>2</sub>Si<sub>4</sub>O<sub>16</sub>·H<sub>2</sub>O?] is massive; probably monoclinic. Perfect cleavage parallel to elongation.  $H. = 7.5$ .  $G. = 2.23$ . The optic plane is normal to the cleavage; extinction is at  $28^\circ$  to cleavage trace.  $Z = b$ .  $(+)2V = 18^\circ$  ca.  $N_Y = 1.67$ ,  $N_Z - N_X = 0.014$ . Color green in mass. Found in veins in schist at Lotru, Transylvania.

<sup>109</sup> C. Palache and L. H. Bauer: *Am. Mineral.*, XII, 373 (1927).

<sup>110</sup> J. E. de Villiers: *Am. Mineral.*, XXVI, 237 (1941).

<sup>111</sup> C. O. Hutton: *Mineral. Mag.*, XXIV, 529 (1937).

<sup>112</sup> J. Irving, M. Vonsen, and F. A. Gonyer: *Am. Mineral.*, XVII, 338 (1932). With 1.11 Fe<sub>2</sub>O<sub>3</sub> and 2.90 FeO.

<sup>113</sup> S. Tsuboi: *Jap. Jour. Geol. Geog.*, XIII, 333 (1936). With 1.74 Fe<sub>2</sub>O<sub>3</sub> and 2.95 FeO.

<sup>114</sup> C. Palache and H. Vassar: *Am. Mineral.*, X, 412 (1925). With 5.29 Fe<sub>2</sub>O<sub>3</sub> and 2.09 FeO.

<sup>115</sup> W. S. Burbank: *Am. Mineral.*, XII, 421 (1927).

<sup>116</sup> V. A. Zavaritsky: *Min. Abst.*, IX, 211 (1946).

<sup>117</sup> G. Munteanu-Murgoci: *Bull. Soc. Fr. Min.*, XXIV, 504 (1901).



(c) WITH ADDITIONAL O ( $\pm$  OTHER ANIONS)—  
("SUBSILICATES")—ANHYDROUS

The "subsiliates" contain  $\text{SiO}_4$  tetrahedrons in their crystal structure, but they contain some additional oxygen atoms not directly connected with Si atoms.

**Beckelite**  $[\text{Ca}_5(\text{Ce}, \text{La}, \text{Di})_4\text{O}_3\text{Si}_3\text{O}_{12}]$  is isometric; crystals cubic, or dodecahedral, with cubic cleavage.  $H. = 5$ .  $G. = 4.15$ .  $F. = 7$ . Soluble in acid. Isotropic with  $N = 1.812$ . Large crystals weakly birefringent. Color yellow to brown. Found in syenite in Balka Wali-Tarana, U.S.S.R.

**SILLIMANITE**

## ORTHORHOMBIC DIPYRAMIDAL



$$a:b:c = 0.980:1:0.757$$

STRUC. Space group  $^{118} Pbnm$ ;  $a$  7.43,  $b$  7.58,  $c$  5.74 Å. U.C. 4.

PHYS. CHAR. Crystals nearly square prisms, vertically striated; terminal faces rare. Perfect 010 cleavage.  $H. = 7.5$ .  $G. = 3.25$ .  $F. = 1816^\circ$ . Insoluble.

OPT. PROP. The optic plane is parallel to 010;  $Z = c$ . The relief is marked and the birefringence rather strong.  $(+)2V = 30^\circ\text{--}25^\circ$ ,  $r > v$  strong. See Fig. 414.  $N_X = 1.655\text{--}1.661$ ,  $N_Y = 1.658\text{--}1.670$ ,  $N_Z = 1.677\text{--}1.684$ ,  $N_Z - N_X = 0.020\text{--}0.023$ .  $F - C$  for  $N_Y = 0.0107$ . The index of refraction is lower in dark-colored crystals; for example, in a pale brown crystal  $^{119} N_X = 1.6612$ , and  $N_Z = 1.6837$ , and in a dark brown crystal  $N_X = 1.6549$ ,  $N_Z = 1.6773$ .

Colorless, yellowish, greenish, brown, blue; the brown color may sometimes be due to scales of biotite.

Colorless in thin section; in thick sections:

X = Pale brownish	Brownish yellow	Very pale yellow
Y = Brown	Grayish green	Colorless or greenish
Z = Dark brown	Violet-blue	Sapphire blue

INVER. Sillimanite dissociates to *mullite* ( $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ ) and liquid at about  $1545^\circ$ . At about  $1810^\circ$  it dissociates to *corundum* ( $\text{Al}_2\text{O}_3$ ) and liquid.

INCL. It often contains inclusions of spinel or biotite or glass.

<sup>118</sup> W. H. Taylor: *Zeit. Krist.*, LXVIII, 503 (1928), and LXXI, 205 (1929).

<sup>119</sup> A fibrous variety (*fibrolite* or *bucholzite*) is said to have much lower indices in some cases, for example  $N_X = 1.629$ ,  $N_Z = 1.635$  ca. E. V. Shannon: *Proc. U. S. Nat. Mus.*, LVIII, 437 (1920).

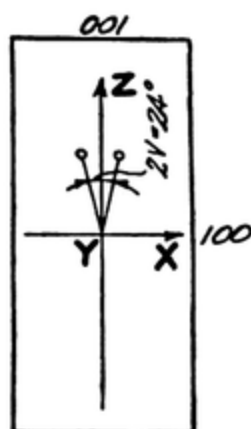


FIG. 414. The optic orientation of sillimanite.



**OCCUR.** It is found chiefly in schists and gneisses; also in eclogite, and near contacts especially of granite. It is formed in igneous rocks probably only as a result of absorption of shales, etc.

**DIAG.** It differs from zoisite and andalusite by the positive elongation, rather strong birefringence, and the optic plane parallel to the cleavage. Interlacing needles are characteristic of the variety called *fibrolite*.

**ANDALUSITE**

ORTHORHOMBIC DIPYRAMIDAL

 $Al_2OSiO_4$  $a:b:c = 0.982:1:0.704$ 

**COMP.**  $Fe^{III}$  and/or  $Mn^{III}$  (and  $Ti?$ ) may proxy for Al to about 10 per cent. With about 10%  $Mn_2O_3$  it is called *viridine* or *manganandalusite*.

**STRUC.** Space group  $^{120}Pnm$ ;  $a$  7.76,  $b$  7.90,  $c$  5.56 Å. U.C. 4.

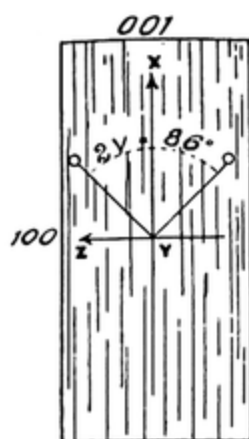


FIG. 415. The optic orientation of andalusite.

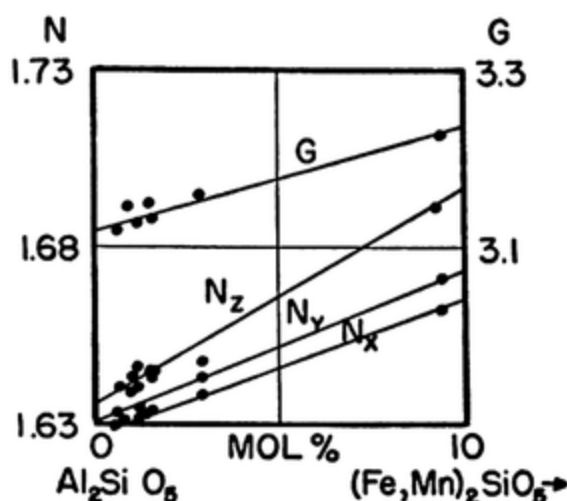


FIG. 416. Properties of andalusite.

**PHYS. CHAR.** Crystals nearly square prisms with good 110 cleavages at  $90^\circ 48'$ .  $H. = 7$  ca.  $G. = 3.1-3.2$ .  $F. = 7$ . Insoluble.

**OPT. PROP.** The optic plane is 010;  $X = c$ . See Fig. 415. Optic angle large about  $X$  with  $r < v$  weak. Data follow (see also Fig. 416):

$\frac{100(Ti + Fe + Mn)}{Ti + Fe + Mn + Al}$	(-)2V	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$	G.	Locality	Authority
0.7	?	1.629	1.633	1.639	0.010	3.13	Gt. Slave L.	Ellsworth <sup>121</sup>
1.1	$86^\circ$	1.634	1.639	1.645	0.011	3.13	Calif.	Macdonald <sup>122</sup>
1.4	?	1.634	1.639	1.643	0.009	3.15	Dolni	Sekanina <sup>123</sup>
2.8	$75^\circ$	1.637	1.641	1.646	0.009	3.16	Calif.	Macdonald <sup>122</sup>
10.3	$71^\circ$	1.662	1.671	1.691	0.029	3.22	Darmstadt	Wülfing <sup>124</sup>

<sup>120</sup> W. H. Taylor: *Zeit. Krist.*, LXXI, 205 (1929).

<sup>121</sup> H. V. Ellsworth and F. Jolliffe: *Univ. Toronto Geol. Stud.*, XL, 71 (1936-1937).

<sup>122</sup> G. A. Macdonald and R. Merriam: *Am. Mineral.*, XXIII, 588 (1938).

<sup>123</sup> J. Sekanina: *Min. Abst.*, IV, 42 (1931).

<sup>124</sup> E. A. Wülfing: *Sitz. Akad. Wiss. Heid.*, 1917A, Abt. 12.

Color red, violet, gray, yellow, green; through alteration may be brown, green, black. Pleochroism variable in intensity even in a single crystal. Colorless in thin section; in thick section:

X = Rose red	Rose red	Blood red	Yellow	Clear yellow
Y = Colorless	Pale yellow	Oil green	Deep green	Grass green
Z = Colorless	Pale yellow	Olive green	Greenish yellow	Dark yellow

INVER. Andalusite changes to mullite and glass at about 1300°.

INCL. Carbonaceous inclusions are characteristic of the variety called *chiastolite*; they are commonly arranged in the crystal in shapes conforming with the symmetry of the mineral.

ALTER. Andalusite alters rather easily to sericite; also, rarely, to a mixture of corundum and spinel with rutile and feldspar.

OCCUR. It is confined chiefly to contacts of igneous rocks with shaly material. Named from Andalusia, Spain, where first found.

DIAG. It is distinguished by its nearly rectangular prismatic cleavages and forms with negative elongation and sign (except *viridine*). Carbonaceous inclusions are common.

**STAUROLITE** ORTHORHOMBIC DIPYRAMIDAL  $\text{HFe}_2\text{Al}_9\text{O}_8\text{Si}_4\text{O}_{16}$   
 $a:b:c = 0.473:1:0.341$

COMP. Mg, Mn, Co, Ni may proxy (in part?) for Fe; a little Fe''' is often present.

STRUC. Space group <sup>125</sup> *Cmcm*;  $a$  7.82,  $b$  16.52,  $c$  5.63 Å. U.C. 2.

PHYS. CHAR. Crystals short prismatic, with {001} and {010}; cruciform twins common, both on 031 <sup>125</sup> giving an apparently rectangular cross and on 231 giving a cross at 60° 31'. See Fig. 417. Distinct 010 cleavage.  $H. = 7-7.5$ .  $G. = 3.65-3.77$ .  $F. = 7$ . Slowly attacked by  $\text{H}_2\text{SO}_4$ ; insoluble in cold dilute HF.

OPT. PROP. The optic plane is 100, and the acute bisectrix  $Z$  is normal to 001. The optic angle varies from about 80° to very nearly 90°, an angle of 86° to 89° being common. See Fig. 418. Dispersion  $r > v$  weak.

$\text{Fe}_2\text{O}_3$	MgO	2V <sub>X</sub>	N <sub>X</sub>	N <sub>Y</sub>	N <sub>Z</sub>	$N_Z - N_X$	G.	Locality	Authority
4.96	2.56	Large	?	1.74 ca.	?	?	3.767	Rhodesia	Skerl <sup>126</sup>
2.76	1.92	90° ca.	1.739	1.744	1.750	0.011	3.775	New Hampshire	Billings <sup>127</sup>
1.80	2.08	88° 21'	1.7393	1.7450	1.7510	0.0118	3.753	St. Gotth.	Hörner <sup>128</sup>
1.59	2.42	86° 28'	1.7436	1.7496	1.7557	0.0121	3.778	Petersdorf	Hörner <sup>128</sup>
2.33	1.78	80° 39'	1.7468	1.7536	1.7621	0.0153	3.759	Bavaria	Hörner <sup>128</sup>

<sup>125</sup> S. Naray-Szabo: *Zeit. Krist.*, LXXI, 103 (1929). The  $c$ -axis is half as long as that shown by Dana, who gives twin laws as 032 and 232. The ideal structural formula is  $\text{H}_2\text{FeAl}_4\text{Si}_2\text{O}_{12}$ .

<sup>126</sup> A. C. Skerl, F. A. Bannister, and A. W. Groves: *Mineral. Mag.*, XXIII, 598 (1934). With 8.48 CoO.

<sup>127</sup> M. P. Billings: *Bull. Geol. Soc. Am.*, XLVIII, 463 (1937).

<sup>128</sup> F. Hörner: *Zeit. Krist.*, LVII, 311 (1922).

Color dark reddish brown, yellowish brown, brownish black. In thin section pleochroism is variable, greater around inclusions, with  $X$  = colorless,  $Y$  = pale yellow,  $Z$  = golden yellow. A variety<sup>126</sup> with 8.48 CoO has  $X$  = cobalt blue,  $Y$  = violet blue,  $Z$  = violet.

**INCL.** Inclusions of quartz are common; rutile, tourmaline, garnet, etc., also occur. In limestones carbonaceous inclusions are found, rarely regularly arranged, much as in chialstolite.

**ALTER.** Staurolite may alter to a green mica of large optic angle or to chlorite.

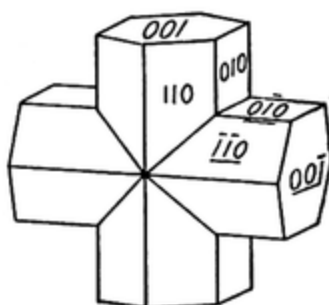


FIG. 417. A cruciform twin of staurolite.

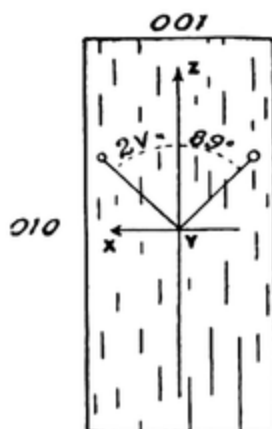


FIG. 418. The optic orientation of staurolite.

**OCCUR.** It is found in schists, phyllites, etc., with garnet, kyanite, andalusite, sillimanite; also in endomorphosed igneous rocks and in exomorphosed sediments.

**DIAG.** In thin section it is characterized by strong absorption in golden yellow tints, parallel extinction, and rather weak birefringence. The crystal forms and twins are also distinctive.

**Kentrolite** ( $Pb_3Mn^{IV}_4O_3Si_3O_{12}$ ) is orthorhombic with  $a:b:c = 0.633:1:0.899$ . Crystals prismatic with distinct 110 cleavage.  $H. = 5$ .  $G. = 6.19$ .  $F. = 2-2.5$ . Soluble in HCl. The optic plane is 010;  $X = a$ .  $(+)2V = 88^\circ$ ,  $r < v$  strong.  $N_X = 2.10$ ,  $N_Y = 2.20$ ,  $N_Z = 2.31$ ,  $N_Z - N_X = 0.21$ . Color dark reddish brown. In section strongly pleochroic in reddish brown with  $X < Y < Z$ . Found in manganese deposits in southern Chile.

#### KORNERUPINE<sup>129</sup>

ORTHORHOMBIC DIPYRAMIDAL

$Mg_{10}Al_{10}BO_7Si_9O_{36}?$

$a:b:c = 0.858:1:0.425$

**COMP.** Fe may proxy for Mg to at least 40 mol. per cent. AlB may proxy for MgSi to about 15 mol. per cent. NaH seems to proxy for Mg to about 10 mol. per cent (in the variety called *prismatine*).

<sup>129</sup> M. H. Hey, B. W. Anderson, and C. J. Payne: *Mineral. Mag.*, XXVI, 119 (1941).

STRUC. Space group  $^{130} Cmmm(?)$ ,  $a$   $^{129}$  13.68,  $b$  15.95,  $c$  6.68 Å. U.C. 2.

PHYS. CHAR. Prismatic masses with distinct 110 cleavage.  $H.$  = 6.5.  $G.$  = 3.27–3.24. Prismatine is fusible; kornerupine nearly infusible ( $F.$  = 6). Insoluble in acids.

OPT. PROP. The optic plane is 100;  $X = c$ . See Fig. 419. Optic angle small with weak dispersion  $r < v$  ( $r > v$  reported once  $^{129}$ ).  $G - B$  for  $N_z$   $^{131}$  = 0.019. Data follow (see Fig. 420):

FeO										
+ Fe <sub>2</sub> O <sub>3</sub>	Na <sub>2</sub> O	2V <sub>X</sub>	N <sub>X</sub>	N <sub>Y</sub>	N <sub>Z</sub>	N <sub>Z</sub> - N <sub>X</sub>	G.	Locality	Authority	
2.04	0.60	20°	1.6613	1.6733	1.6742	0.0129	3.28	Madagascar	Lacroix <sup>132</sup>	
8.1	Trace	20.5°	1.669	1.681	1.682	0.013	3.335	Ceylon	Hey <sup>129</sup>	
12.3	1.6	0°	1.675	1.687	1.687	0.014	3.37	Saxony	Hey <sup>129</sup>	
12.22	0.7	48°	1.682	1.696	1.699	0.017	3.445	Natal	de Villiers <sup>37</sup>	

Color white, yellow, brown, sea green. In thin section colorless or pleochroic with  $X$  = pale brown, green, reddish yellow,  $Y$  = yellow, pale brownish yellow, dark green,  $Z$  = dark green, pale brownish green, brown, pale green.

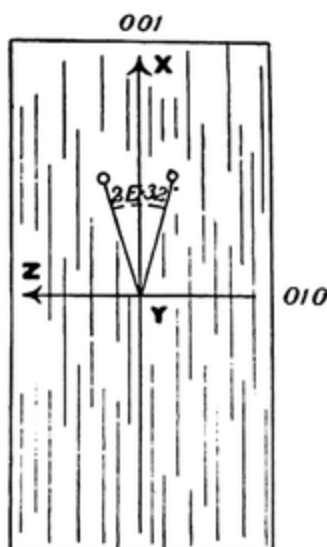


FIG. 419. The optic orientation of kornerupine.

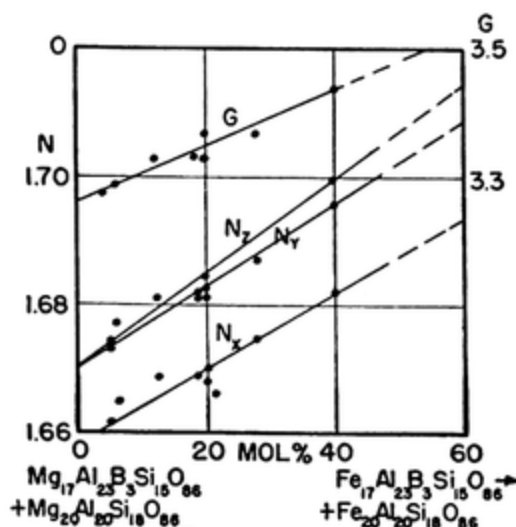


FIG. 420. Properties of kornerupine.

ALTER. Prismatine alters to a green fibrous mineral known as *kryptotile*, which is related to mica; it has  $H.$  = 2–3,  $G.$  = 3.05,  $F.$  = 6, soluble in cold HF, birefringent; indices unknown.

OCCUR. Kornerupine is found in schists with cordierite and sapphirine; also in pegmatite and "granulite." Found at Fiskernäs, Greenland; Waldheim, Saxony; etc.

DIAG. It differs from sillimanite in having negative elongation and weaker birefringence, from andalusite in higher refringence and smaller optic angle, and from topaz in prismatic cleavage, higher relief, and negative elongation.

<sup>130</sup> B. Gossner and F. Mussnug: *N. Jahrb. Min.*, A, Bl. Bd. LVIII, 227 (1928).

<sup>131</sup> C. J. Payne: *Min. Abst.*, VII, 518 (1940).

<sup>132</sup> A. Lacroix: *C. R. Acad. Sci. Paris*, CLV, 672 (1912); *Bull. Soc. Fr. Min.*, LXII, 300 (1939).

**Melanotekite** ( $Pb_3Fe''_4O_3Si_3O_{12}$ ) is orthorhombic with  $a:b:c = 0.634:1:0.913$ . Crystals prismatic with two unequal cleavages.  $H. = 6.5$ .  $G. = 5.7$ .  $F. = 2-2.5$  with intumescence. Decomposed by  $HNO_3$ . Optic orientation unknown.  $(+)2V = 67^\circ$ ,  $r < v$  rather strong.  $N_X = 2.12$ ,  $N_Y = 2.17$ ,  $N_Z = 2.31$ ,  $N_Z - N_X = 0.19$ . Color black; in thin section intensely pleochroic with  $X =$  nearly colorless,  $Y =$  pale reddish brown,  $Z =$  deep reddish brown. Found in lead ore deposits as at Pajsberg, Sweden, and Hillsboro, New Mexico.

**Katoptrite**<sup>133</sup>  $[(Mn,Mg,Fe)_{14}Sb_2O_3(Al,Fe)_4O_{16}Si_2O_8?]$  is monoclinic with  $a:b:c = 0.792:1:0.490$ ,  $\beta = 101^\circ 3'$ . Crystals {010} tablets with perfect 100 cleavage.  $H. = 5.5$ .  $G. = 4.5$ . Insoluble in acid. The optic plane is 010;  $X \wedge c = 14^\circ-15^\circ$  with strong inclined dispersion.  $(-)2V = 25^\circ ca.$ ,  $r > v$ .  $N_Y = 1.9$  (est.),  $N_Z - N_X = ?$  Color black; luster metallic, in section pleochroic, dark red-brown nearly parallel to  $X$  and red-yellow parallel to  $Y$ . Found in contact deposits in limestone at Nordmarken, Sweden.

## SPHENE (*Titanite*) MONOCLINIC PRISMATIC



$$a:b:c = 0.755:1:0.854 \quad \beta = 119^\circ 43'$$

**COMP.** Sphene may contain 1 to 20%  $R_2O_3$  doubtless as  $R_2SiO_5$ ;  $R$  may be  $Fe''$ ,  $Al$ ,  $Y$ ,  $Ce$ ,  $Cb$ ,  $Na$ . A little  $Ti$  may proxy for  $Si$  (when  $Ti > Si$ ). The variety *keilhauite* contains up to about 12%  $(Y,Ce)_2O_3$ . One  $O$  atom may be replaced<sup>134</sup> in part by  $OH$  and  $F$ .

**STRUC.** Space group<sup>135</sup>  $C2/c$ ;  $a$  6.55,  $b$  8.70,  $c$  7.43 Å. U.C. 4.

**PHYS. CHAR.** Crystals often wedge-shaped (whence the name) with large {001} and {111} faces; very varied; may be pyramidal or elongated along  $c$  or  $a$ . Twinning on 100; also lamellar on 221, due to shearing stress (the twinning may be produced artificially at 3000 atm.), causing parting. Distinct 110 cleavage.  $H. = 5-5.5$ .  $G. = 3.4-3.56$ .  $F. = 3$ . Soluble in  $H_2SO_4$ .

**OPT. PROP.** The optic plane is 010;  $Z$  is nearly normal to 102, making an angle of about  $51^\circ$  ( $47^\circ-57^\circ$ ) with  $c$  (cleavage) in the obtuse angle  $\beta$  (see Fig. 421). The optic angle is variable ( $23^\circ-55^\circ$ ) but usually small with extreme axial dispersion ( $r > v$ ) and weak inclined dispersion. Data are still insufficient to show relations between variations in composition and in optic properties, but in general indices of refraction

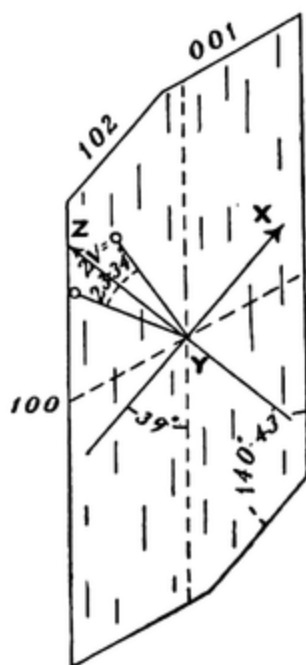


FIG. 421. The optic orientation of sphene.

<sup>133</sup> G. Flink: *Geol. För. Förh. Stockholm*, XXXIX, 431 (1917).

<sup>134</sup> T. G. Sahama: *C. R. Soc. Géol. Finlande*, XIX, 88 (1946); also *Bull. Com. Géol. Finlande*, 138 (1946). H. W. Jaffe: *Am. Mineral.*, XXXII, 637 (1947).

<sup>135</sup> W. Zachariasen: *Zeit. Krist.*, LXXIII, 7 (1930).

decrease and the optic angle increases with decrease of Ti. Data follow:

TiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	Al <sub>2</sub> O <sub>3</sub>	(Ce,Y) <sub>2</sub> O <sub>3</sub>	2VZ	N <sub>X</sub>	N <sub>Y</sub>	N <sub>Z</sub>	N <sub>Z</sub> - N <sub>X</sub>	Z $\wedge$ c	Authority
40.89	0.00	0.00	Trace	23° ca.	1.901	?	2.093	0.182	51°	Sahama <sup>134</sup>
40.10	0.40	0.27	?	20°—	1.950	1.970	2.092	0.142		Bohnstedt <sup>136</sup>
35.26	1.34	1.02	4.51	33° calo.	1.90	2.04 ca.	2.04 ca.	0.14	36°	Morgante <sup>137</sup>
33.70	0.20(FeO)	4.44	0.30	38°	1.84	?	1.975	0.135	50°	Sahama <sup>134</sup>
30.65	6.17	7.32	3.58	35°-40°	1.843	1.870	1.943	0.100		Young <sup>138</sup>

The third sample above is called *grothite*, and the fourth is *keilhauite*; indices in these cases are lowered by Al<sub>2</sub>O<sub>3</sub> (and F).

In zonal growths the refringence and optic angle may increase from the center to the border.

Color brown, yellow, gray, green, rose-red, black, often varying in a single crystal. Pleochroism usually weak (or absent) in thin section, but deeply colored types show marked pleochroism, especially in thick sections, as follows:

X = Greenish yellow	Pale brownish yellow	Nearly colorless
Y = Greenish pink	Pale brownish yellow	Greenish yellow
Z = Salmon pink	Pale yellow	Orange brownish red

INCL. Ripidolite lamellae, which may be grouped at the center, form rare inclusions in sphene; albite inclusions are also known.



FIG. 422. Photomicrograph of sphene in thin section.

ALTER. Sphene may lose its color, become softer, and turn into a light yellow aggregate called *leucoxene*,<sup>139</sup> or it may be replaced by an opaque iron oxide with more or less ilmenite, rutile, calcite, etc.

OCCUR. It is very widely, but sparsely, distributed in rocks of all kinds. It is particularly common in hornblende granites, syenites, and diorites, as well as in schists and gneisses. See Fig. 422. It is rare in sediments.

DIAG. Sphene is characterized by its wedge-shaped forms, ex-

<sup>136</sup> E. Bohnstedt: *Trans. Lomonosov Inst.*, VII, 49 (1936); *Min. Abst.*, VII, 210 (1939).

<sup>137</sup> S. Morgante: *Min. Abst.*, IX, 216 (1946).

<sup>138</sup> J. A. Young: *Am. Mineral.*, XXIII, 149 (1938).

<sup>139</sup> Leucoxene is usually an aggregate of rutile needles. See S. A. Tyler and R. W. Marsden: *Jour. Sed. Petrol.*, VIII, 55 (1938).



treme refringence and birefringence, strong axial dispersion, and positive sign.

**Fersmanite**<sup>140</sup> ( $Na_2CbOFSiO_4$  with  $Ca_2TiO_2SiO_4$ ,  $CaMnTiO_2SiO_4$ , etc.) is monoclinic with  $a:b:c = 0.991:1:0.996$ ,  $\beta = 97^\circ 16'$ . Crystals pseudotetragonal with  $H. = 5.5$ .  $G. = 3.44$ . The optic plane is 010; X nearly normal to 001.  $(- )2V = 0^\circ - 7^\circ$ ,  $N_X = 1.886$ ,  $N_Y = 1.930$ ,  $N_Z = 1.939$ ,  $N_Z - N_X = 0.053$ . Brown, weakly pleochroic. Found with feldspar, nepheline, and acmite in the Khibina tundra, U.S.S.R.

**Lamprophyllite**<sup>141</sup> [ $Na_3(Sr,Ca,Fe,Mn)Ti_3O_2OHSi_3O_{12}?$ ] is monoclinic<sup>142</sup> with  $a:b:c = 0.923:1:0.605$ ,  $\beta = 102^\circ 43'$ . *Molengraafite* is a variety containing some  $Al_2O_3$ . Crystals usually {100} plates, vertically elongated. Distinct 100 and poor 010 cleavages. Lamellar twinning on 100.  $H. = 2-3$ .  $G. = 3.45-3.54$ . The optic plane and X are normal to 010;  $Z \wedge c = 4^\circ$  ca. to  $8^\circ$ .  $(+)2V = 23^\circ-41^\circ$ .  $r > v$  strong.  $N_X = 1.735-1.746$ ,  $N_Y = 1.747-1.754$ ,  $N_Z = 1.770-1.779$ ,  $N_Z - N_X = 0.032-0.035$ . Color yellow to brown or gray with X = yellow, Y = straw yellow or colorless, Z = orange or straw yellow. Found in nepheline syenite of the Bearpaw Mountains, Montana, and the Kola Peninsula, U.S.S.R.

**Serendibite**<sup>143</sup> [ $Ca_2(Mg,Fe)_4Al_6B_2O_{16}Si_4O_{16}?$ ] is probably triclinic, with lamellar twinning like plagioclase. No cleavage.  $H. = 6.5-7$ .  $G. = 3.42$ .  $F. = 7$ . Nearly insoluble in acid. Sections normal to twinning and nearly normal to Z have extinction at  $35^\circ$  to  $40^\circ$ .  $(+)2V =$  nearly  $90^\circ$  (also negative),  $r < v$  strong.  $N_X = 1.701$ ,  $N_Y = 1.703$ ,  $N_Z = 1.706$ ,  $N_Z - N_X = 0.005$  (Larsen<sup>143</sup>);  $N_X = 1.719$ ,  $N_Y = 1.722$ ,  $N_Z = 1.724$ ,  $N_Z - N_X = 0.005$  (Richmond<sup>144</sup>). Color sky to indigo blue with X = pale yellow-green, Y = pale blue-green or nearly colorless, Z = bright sky blue or Prussian blue. Found in contact zones in Ceylon and in Warren County, New York.

**KYANITE**<sup>145</sup> (*Disthene*) TRICLINIC PINACOIDAL  $Al_2OSiO_4$   
 $a:b:c = 0.907:1:0.710$      $\alpha = 89^\circ 58.5'$      $\beta = 101^\circ 8'$      $\gamma = 105^\circ 57'$

COMP. A little  $Na_2O$  and  $K_2O$  and  $H_2O$  are commonly present;<sup>146</sup> also  $Fe'''$ , Ca.

STRUC. Space group<sup>147</sup>  $P\bar{1}$ .  $a$  7.09,  $b$  7.72,  $c$  5.56 Å. U.C. 4.

PHYS. CHAR. Crystals {100} tablets elongated parallel to  $c$ ; terminations rare. See Fig. 423. Perfect 100 and good 010 cleavages; 001 parting. Twinning often lamellar with 100 as the composition face and the twinning axis either normal to 100 or parallel to  $b$  or  $c$ ; also multiple

<sup>140</sup> I. D. Starinkevitch-Borneman: *Min. Abst.*, VII, 209 (1939).

<sup>141</sup> E. Bohnstedt: *Min. Abst.*, V, 34 (1932).

<sup>142</sup> B. Gossner and K. Drexler (*Zeit. Krist.*, XCI, 494, 1935) by X-ray study conclude that lamprophyllite is orthorhombic with  $a$  19.05,  $b$  7.05,  $c$  5.35 Å. This conclusion is questioned by W. T. Pecora (*Am. Mineral.*, XXVII, 397, 1942).

<sup>143</sup> E. S. Larsen and W. T. Schaller: *Am. Mineral.*, XVII, 457 (1932).

<sup>144</sup> G. M. Richmond: *Am. Mineral.*, XXIV, 725 (1939).

<sup>145</sup> L. Barić: *N. Jahrb. Min.*, LXXVIA, 36 (1940).

<sup>146</sup> J. Jakob: *Schw. Min. Pet. Mit.*, XXI, 131 (1941).

<sup>147</sup> S. Náray-Szabo, W. H. Taylor, and W. W. Jackson: *Zeit. Krist.*, LXXI, 117 (1929).

twinning on 001 may be produced by pressure. Crystals distinctly flexible and often bent or twisted. On 100,  $H. = 4-5$  parallel to  $c$  and 6-7 parallel to  $b$ ; on 010,  $H. = 6$  parallel to  $c$  and 7 normal to  $c$ ; on 001,  $H. = 5.5$  parallel to  $b$  and 6.5 parallel to  $a$ ; on  $1\bar{1}0$ ,  $H. = 7.5$ .  $G. = 3.6$  ca.  $F. = 7$ . Insoluble.

OPT. PROP. The negative acute bisectrix  $X$  is nearly normal to 100; extinction on 100,  $Z' \wedge c = 27^\circ-32^\circ$ ; extinction on 010,  $Z' \wedge c = 5^\circ-8^\circ$ ;

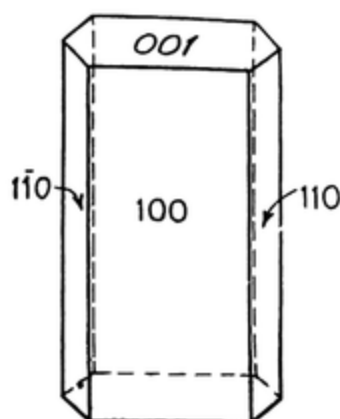


FIG. 423. A bladed crystal of kyanite.

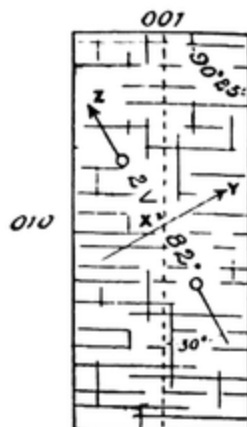
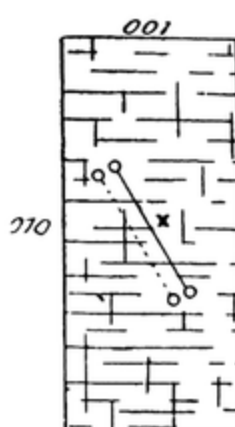


FIG. 424. Approximate optic orientation of kyanite.



FIGS. 425, 426. Approximate optic orientation of kyanite twinned on an axis (1) normal to 100, and (2) normal to  $100:001$  or  $100:010$ .

extinction on 001,  $X' \wedge a = 0^\circ-2.5^\circ$ . See Figs. 424-426.  $(- )2V = 82.5^\circ$  ca.,  $r > v$  weak, with weak inclined and distinct crossed dispersion. Data follow:

$Fe_2O_3$	$(Na,K)_2O$	$H_2O$	$2V_X$	$N_X$	$N_Y$	$N_Z$	$N_Z - N_X$	$G.$	Authority
0.30	?	0.03	$82^\circ 15'$	1.7131	1.7219	1.7285	0.0154	3.65	Barić <sup>145</sup>
0.33	1.10	0.83	?	1.717	1.722	1.729	0.012	3.53	Gubelin <sup>148</sup>
0.34	?	?	$82^\circ$	1.718	?	1.734	0.014	?	Ozerov <sup>149</sup>

Color blue (whence the name), white, rarely gray, green, black. Colorless in thin section, but in plates 0.5 to 1 mm. thick it may be pleochroic with  $X$  = colorless,  $Y$  = violet blue,  $Z$  = dark cobalt blue. Color may disappear on heating.

INVER. Kyanite changes slowly (but more easily than andalusite) to mullite and glass at temperatures above  $1300^\circ$ .

ALTER. It alters readily to muscovite, sometimes with chlorite.

OCCUR. It is found only in schists and pegmatites cutting schists, as at Villa Rica, Brazil; Donegal, Ireland; and Thetford, Vermont.

<sup>145</sup> E. Gubelin: *Schw. Min. Pet. Mit.*, XIX, 325 (1939).

<sup>149</sup> K. N. Ozerov and N. A. Bykhover: *Min. Abst.*, VII, 49 (1938). With 1.81  $Cr_2O_3$  and 1.10  $TiO_2$ . *Trans. Centr. Geol. Prosp. Inst.*, No. 82 (1936).

**DIAG.** It is distinguished by numerous cleavage lines, high relief, moderate birefringence, and extinction at about  $30^\circ$  to 010 cleavage in sections normal to the acute bisectrix X; this extinction is at about  $60^\circ$  to the basal parting.

**Yeatmanite**<sup>150</sup>  $[(Mn,Zn)_{16}O_{10}Sb_2O_3Si_4O_{16}]$  is triclinic with  $a:b:c = 0.781:1:0.478$ ,  $\alpha = 103^\circ 49'$ ,  $\beta = 101^\circ 45'$ ,  $\gamma = 87^\circ 12'$ .  $a$  9.029,  $b$  11.56,  $c$  5.52 Å. U.C. 1. Crystals pseudo-orthorhombic with twinning on 023 and multiple twinning on 010. Perfect 100 cleavage.  $H. = 4$ .  $G. = 5.0$ . X is near  $a$ , Y is near  $b$  while  $Z \wedge c = 3.5^\circ$ .  $(- )2V = 49^\circ$  ca.  $r < v$  moderate.  $N_X = 1.873$ ,  $N_Y = 1.905$ ,  $N_Z = 1.910$ ,  $N_Z - N_X = 0.037$ . Found in the ore deposit at Franklin, New Jersey.

(c) WITH ADDITIONAL O ( $\pm$  OTHER ANIONS)—  
("SUBSILICATES")—HYDROUS

**Långbanite**<sup>150a</sup>  $(Mn''_4Mn^{IV}_3O_8 \cdot SiO_4?)$ , with some Sb and Ca proxying for  $Mn''$  and some  $Fe'''$  and Mg for  $Mn^{IV}$  is dihexagonal dipyramidal with  $c/a = 0.961$ ; space group  $C6/mmm$ ;  $a$  11.54,  $c$  11.09 Å. U.C. 4. Crystals complex and varied without cleavage.  $H. = 6.5$ .  $G. = 4.6-4.8$ .  $F. = 7$ . Slowly soluble in HCl. Uniaxial and negative with  $N_O = 2.36$ ,  $N_E = 2.31$ ,  $N_O - N_E = 0.05$  Li. Color black; slightly pleochroic in section in dark reddish brown with  $O > E$ . Found in ore deposits at Långban, Sweden.

**Ardennite**  $[(Mn,Ca)_5Al_5(As,V)O_4(OH)_2Si_5O_{20} \cdot 2H_2O?]$  is orthorhombic dipyramidal with  $a:b:c = 0.470:1:0.314$ . Space group<sup>151</sup> probably  $Pmmn$ ;  $a$  8.72,  $b$  18.56,  $c$  5.83 Å. U.C. 2. Crystals prismatic with perfect 010 and distinct 110 cleavages; also 001 parting.  $H. = 6$ .  $G. = 3.6-3.65$ .  $F. = 2-2.5$ . Insoluble in HCl. The optic plane is 100;  $Z = b$  (Larsen<sup>152</sup>); see Fig. 427; the optic plane is 010;  $Z = c$  (Lacroix<sup>153</sup>).  $(+)2V = 0^\circ-50^\circ$  (Larsen<sup>152</sup>);  $(+)2V = 68^\circ-70^\circ$  (Lacroix<sup>153</sup>);  $N_Y = 1.74$  ca. to 2.0 ca. (Larsen<sup>153</sup>),  $N_Z - N_X = 0.015-0.02$ . Color yellow to brown with<sup>154</sup> X = dark brownish yellow, Y = golden yellow, Z = pale yellow. Found in veins and pegmatites, as in the Ardennes, Belgium, and in the Piedmont.

**Uranophane** or  $\alpha$ -uranotile  $(CaU_2O_3Si_2O_8 \cdot 7H_2O)$  is orthorhombic with  $a:b:c = 0.307:1:1$  ca. Crystals prismatic with one cleavage or flat

<sup>150</sup> C. Palache, L. H. Bauer, and H. Berman: *Am. Mineral.*, XXIII, 527 (1938).

<sup>150a</sup> H. Strunz: *Zent. Min.*, 1942A, 133.

<sup>151</sup> B. Gossner and H. Strunz: *Zeit. Krist.*, LXXXIII, 415 (1932). The  $abc$  axes of Gossner and Strunz are changed above to  $bca$  to make  $b > a > c$ . Relation of these axes to cleavages is not known certainly.

<sup>152</sup> E. S. Larsen: *U. S. Geol. Surv. Bull.* 679 (1921); E. S. Larsen and H. Berman: *U. S. Geol. Surv. Bull.* 848 (1934). For ardennite with  $N_Y = 1.74$  Larsen gives X or Y =  $c$  and Z =  $a$ .

<sup>153</sup> A. Michel Lévy and A. Lacroix: *Les Minéraux des Roches*, 155 (1888).

<sup>154</sup> Cesàro and Abraham (*Ann. Soc. Géol. Belg.*, XXXVI, M 197, 1909) state that ardennite can be distinguished from carpholite by its total lack of pleochroism!

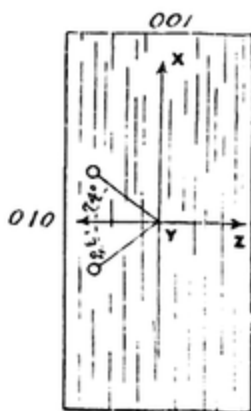


FIG. 427. The optic orientation of ardennite with  $N_Y$  about 1.78.

face.  $H. = 2-3$ .  $G. = 3.8-4$ .  $F. = 7$ . Gelatinizes with HCl.  $X$  is normal to the cleavage.  $Z = c$  (elongation).  $(-)2V = 32^\circ-45^\circ$ ,  $r < v$  extreme.  $N_X = 1.643$ ,  $N_Y = 1.666$ ,  $N_Z = 1.669$ ,  $N_Z - N_X = 0.026$ . Abnormal blue interference color due to strong dispersion. Color yellow with  $X =$  nearly colorless,  $Y =$  pale canary yellow,  $Z =$  canary yellow. Found in pegmatite, as at Kupferberg, Silesia.

**Sklodowskite** <sup>155</sup> ( $MgU_2O_3Si_2O_8 \cdot 7H_2O$ ) is orthorhombic with  $a:b:c = 0.311:1:1.05$ . Crystals long prismatic with basal cleavage.  $G. = 3.54$ . Gelatinizes with HCl. Contains some Ni, K, and Na. The optic plane is 001;  $X = a$ .  $(-)2V =$  very large,  $r < v$  distinct.  $N_X = 1.613$ ,  $N_Y = 1.635$ ,  $N_Z = 1.657$ ,  $N_Z - N_X = 0.044$ . Color yellow with  $X =$  colorless,  $Y =$  pale yellow,  $Z =$  yellow. Found in uranium ore in the Congo (Katanga).

**Cuprosklodowskite** <sup>156</sup> ( $CuU_2O_3Si_2O_8 \cdot 6H_2O$ ) is similar, with  $N_X = 1.654$ ,  $N_Z < 1.664$ . Also reported as  $N_X = 1.655$ ,  $N_Y = N_Z = 1.667$ .

**Soddyite** <sup>157</sup> ( $U_5Si_2O_{19} \cdot 6H_2O$ ) is orthorhombic with  $a:b:c = 0.796:1:1.669$ . Crystals prismatic.  $H. = 3-4$ .  $G. = 4.63$ . Biaxial negative with  $N_X = 1.645$ ,  $N_Y = 1.662$ ,  $N_Z = ?$ . Rarely pleochroic. Found with curite and torbernite at Kasolo in the Congo.

**$\beta$ -Uranotile** <sup>158</sup> ( $CaU_2O_3Si_2O_8 \cdot 6H_2O$ ) is monoclinic in minute needles with  $\beta =$  about  $94^\circ$ . May show zonal growth. Common twinning (on 100). Perfect 010 and poor 100 cleavages.  $G. = 3.95$ . The optic plane and  $X$  are normal to 010;  $Z \wedge c = 30^\circ-60^\circ$ , varying much with wave length of light and also in different zones, being smaller in zones of higher refringence. In white light the crystals show abnormal interference colors and no position of complete extinction. Optic angle large with  $r > v$  and strong crossed dispersion. Data follow:

B		D		F		F - B
$(-)2V = 63.5^\circ$	$(63^\circ-73^\circ)$	$62^\circ$	$(45^\circ-71^\circ)$	$60^\circ$	$(60^\circ-70^\circ)$	$-3.5^\circ$
$N_X = 1.661$	$(1.659-1.668)$	1.663	$(1.661-1.671)$	1.668	$(1.665-1.674)$	0.007
$N_Y = 1.684$	$(1.674-1.685)$	1.688	$(1.682-1.694)$	1.693	$(1.692-1.702)$	0.009
$N_Z = 1.691$	$(1.682-1.694)$	1.697	$(1.689-1.702)$	1.707	$(1.700-1.713)$	0.016
$N_Z - N_X = 0.030$	$(0.023-0.030)$	0.034	$(0.028-0.034)$	0.039	$(0.035-0.046)$	0.009
$Z \wedge c = 36^\circ$	$(36^\circ-60^\circ)$	$32.5^\circ$	$(32^\circ-57^\circ)$	$29.5^\circ$	$(29^\circ-55^\circ)$	$-6.5^\circ$

Color yellow to green with strong pleochroism;  $X =$  nearly colorless,  $Y = Z =$  deep yellow. Found in pegmatite, as at Bedford, New York.

**Kasolite** <sup>159</sup> [ $Pb_2U_2O_4Si_2O_8 \cdot H_2O?$ ] is monoclinic with  $a:b:c = 1.895:1:0.957$ ,  $\beta = 104^\circ 42'$ .  $a$  13.28,  $b$  7.01,  $c$  6.75 Å. U.C. 4. Crystals elongated along  $b$ . Perfect 001 and poor 100 and 010 cleavages.  $H. = 4-5$ .  $G. = 6.46$ .  $F. =$  easy. Gelatinizes with acid.  $X = b$ ;  $Z \wedge c = 1^\circ$  ca.  $(+)2V = 43^\circ 18'$  Na,  $42^\circ 58'$  Li;  $N_X = 1.89$  (calc.),  $N_Y = 1.90$ ,  $N_Z = 1.967$  (calc.).  $N_Z - N_X = 0.077$  (calc.). Color ochre yellow in thin section; not pleochroic. Found in ore deposits in the Belgian Congo.

*Alumina-silica hydrogels* are apparently amorphous and isotropic with  $N = 1.48-1.68$  after ignition, decreasing with increasing silica; thus, if  $Al_2O_3:SiO_2 = 1:0$ ,

<sup>155</sup> A. Schoep: *Bull. Soc. Fr. Min.*, XLVII, 162 (1924); *Min. Abst.*, III, 371 (1927).

<sup>156</sup> R. Nováček: *Min. Abst.*, VI, 148 (1935); *N. Jahrb. Min.*, I, 141 (1936).

<sup>157</sup> A. Schoep: *C. R. Acad. Sci. Paris*, CLXXIV, 1066 (1922). *Bull. Soc. Belge Géol.*, XXXIII, 83 (1923). *Min. Abst.*, III, 371 (1927).

<sup>158</sup> V. Steinocher and R. Nováček: *Am. Mineral.*, XXIV, 324 (1939).

<sup>159</sup> V. Billiet and W. F. de Jong: *Min. Abst.*, VI, 429 (1937); J. Mélon: *Bull. Acad. Roy. Belg.*, 1934, 178.

$N = 1.68$ ;  $1:0.9$ ,  $N = 1.58-1.595$ ;  $1:1.9$ ,  $N = 1.535-1.545$ ;  $1:2.8$ ,  $N = 1.520-1.539$ ;  $1:4.3$ ,  $N = 1.494-1.595$ ;  $1:6.5$ ,  $N = 1.48-1.49$ ;  $0:1$ ,  $N = 1.48-1.485$  (Splichal<sup>160</sup>). Some such hydrogels have been described, as follows:

*Allophane* ( $Al_2O_3 \cdot SiO_2 \cdot nH_2O?$ ) is probably amorphous.  $H. = 3$ .  $G. = 1.85-1.89$ .  $F. = 7$ . Gelatinizes with  $HCl$ . Isotropic with  $N = 1.47-1.49$ . After ignition,<sup>160</sup>  $N = 1.50-1.57$ . Allophane with  $7.97 P_2O_5$  has  $N = 1.495-1.500$  (Gordon<sup>161</sup>). Color blue, green, brown, white, color being due to impurities. It forms hyaline crusts and masses in coal and ore deposits; found at Schneeberg, Saxony; Kent, England; Richmond, Massachusetts; etc.

*Schroetterite* ( $3Al_2O_3 \cdot SiO_2 \cdot nH_2O?$ ) is apparently amorphous.  $H. = 3-3.5$ .  $G. = 2$  ca.  $F. = 6$ . Slowly soluble in  $HCl$ . Isotropic with  $N = 1.584$ . Color white, green, brownish. Like opal or gum. Found in clay or limestone, as at Sand Mountain, Alabama.

*Aidyrlite*<sup>162</sup> ( $2NiO \cdot 2Al_2O_3 \cdot 3SiO_2 \cdot 7.5H_2O?$ ) gives distinct X-ray pattern but is isotropic or weakly birefringent with  $H. = 2.5$  and  $N$  usually  $= 1.533$  to  $1.545$ , but also  $1.509$  to  $1.573$ . Forms gel aggregates of turquoise-blue color; found in veins in limestone at Aidyrly in the Urals.

<sup>160</sup> J. Splichal: *Min. Abst.*, I, 288 (1922).

<sup>161</sup> S. G. Gordon: *Proc. Acad. Sci. Phila.*, XCVI, 279 (1944).

<sup>162</sup> M. Godlevsky: *Min. Abst.*, VI, 150 (1935).





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